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Technical Report LEVEL II

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PERIPHERAL DETECTION AND IDENTIFICATION OF SELF-LUMINOUS DISPLAY VARIATIONS IN 'OCEAN' AND 'HARBOR' VIEWING ENVIRONMENTS

W. S. Vaughan, Jr.
Robert A. Glass
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Contract Number: N00014-74-C-0276
Work Unit Number: NR 196-134

Prepared for:

Engineering Psychology Programs
Psychological Sciences Division
Office of Naval Research
Arlington, Virginia 22217

Prepared by:

OCEANAUTICS, Inc.

422 Sixth Street
Annapolis, Maryland 21403

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November 1978

Technical Report

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Effectiveness of a range of peripheral angles was examined for two visual tasks (detection and identification) and three display characteristics (console distance, color and luminance) in two kinds of underwater viewing environments, 'Ocean' and 'Harbor'. Peripheral angles ranged between 7 deg and 56 deg at six values for each of three Console Distances (25, 35 and 45 cm). All display locations were along the horizontal meridian perpendicular to the line of sight. over

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Display Colors were Green and Red (Wratten filters #65 and #26). Display luminance was 100 ft-L in the 'Harbor' turbidity condition and 0.1 ft-L in the 'Ocean'. At the 35 cm Console Distance, display luminances of 30 ft-L and 0.03 ft-L were included. The two underwater viewing environments were simulations of the physical characteristics of suspended particles or organic materials which occur in natural oceans and harbors. Twelve

Dark-adapted Observers, twelve in number, performed a continuous compensatory tracking task and monitored their performance by attending to a tracking display positioned along the line of sight at 0 deg eccentricity. After a few seconds of tracking, a self-luminous, 5-segment digit appeared at one of six peripheral locations. Observer indicated detection of the peripheral signal, by a button press and identification of the digit by naming the number displayed Reaction time between signal onset and button press was counted in milliseconds and used as a measure of detection performance; percent of the twelve observers accurately identifying the displayed digit for a given combination of display variables was the measure of identification performance. Maximum duration of the display was three seconds.

Green display Color was significantly more effective than Red in peripheral effectiveness for the detection task in both turbidity conditions. Color differences were relatively unimportant to peripheral identification, although Green was consistently equal or superior to Red. The identification task was sensitive to differences in Console Distance; a Console Distance of 35 cm supported a wider useful periphery than either the 25 cm or the 45 cm distances. In the 'Harbor' turbidity environment, a 1/2 log reduction in display luminance substantially reduced the peripheral effectiveness of Red relative to Green for both visual tasks. The optimally effective combination of display characteristics, in both 'Ocean' and 'Harbor' turbidity environments, was a high intensity, green display viewed at an eye-to-console distance of 35 cm (14 inches). Given these design conditions, detection was within 500 msec reaction time to a peripheral location 37.5 cm (14.75 inches) from line of sight; identification was at least 90% accurate within 21.6 cm (8.5 inches) of console center.

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ACKNOWLEDGMENTS

Inquiry into the general problem area of which this experiment is one part has been long encouraged by Mr. Gerald S. Malecki, ONR scientific officer; by CDR I. C. LeMoyne of OPNAV 323; and by LCDR J. W. Schropp of NAVSEA (00C-3). Their sustained support is most gratefully appreciated.

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We are indebted to Mr. Allan Slater who designed the test tank, the optical system, and the control and recording apparatus. Dr. Kent Boyd advised about the experimental design and Ms. A. S. Mavor gave much time to the data analysis.

PERIPHERAL DETECTION AND IDENTIFICATION OF SELF-LUMINOUS DISPLAY VARIATIONS IN 'OCEAN' AND 'HARBOR' VIEWING ENVIRONMENTS

I. INTRODUCTION

Because the design of the human eye has evolved to process light travelling through an air medium, focused vision underwater requires that the diver wear some form of facemask. One potential disadvantage of this requirement is the restricted usefulness of peripheral visual fields underwater vis-a-vis normal, in-air, task environments. In normal viewing environments, peripheral visual fields are limited by the anatomical features of the face; underwater peripheral field limits are determined by the design of the particular mask. These limits are documented by several perimetry studies of observers in air environments (Taylor, 1972, presents summaries), and by one study underwater (Weltman, et al, 1965). The in-air perimetry studies account for a range of variations in permissible head and eye movements; the underwater perimetry study used the head-fixed, eyes-free-to-move viewing condition and assessed three masks with dark-adapted observers and a white light stimulus, two masks with light-adapted observers and a pencil point stimulus. In general, facial features restrict the peripheral areas of the visual field lying above the horizontal meridian (270°-90°), and permit greatest range of vision along the horizontal meridian and those meridians adjacent to the horizontal. Facemasks tend to be most restrictive in the lower half of the visual field, i.e., along all meridians below the horizontal.

Additional in-air studies of peripheral response characteristics have included visual tasks other than detection, and variations in signal luminance and wavelength. These studies used reaction time as a measure of peripheral sensitivity and yielded functional relationships with peripheral angle rather than limits based on detect/non-detect response alternatives. In general, reaction

time to visual signals is fastest at the fovea and becomes progressively slower as peripheral angle increases. However, with a dark-adapted eye and low intensity, small-size stimuli, reaction time tends to correspond to the density distribution of rod receptors in the retina, i.e., fastest at 20° eccentricity and slower at both smaller or larger angles (Rains, 1963). At photopic levels of signal luminance, reaction time is faster to the higher luminance signals (Rains, 1963; Bartlett, et al, 1968).

Color or wavelength of the light makes a difference to peripheral responsiveness. Haines, et al, 1974, showed that red light (632 nm) at .025 ft-L luminance yielded slower reaction times than blue (464 nm) or green (526 nm) light at .025 ft-L at all peripheral locations tested. Further, as peripheral angle increased, the rate of increase in reaction time was significantly greater for red than for blue or green light. In a later study, Haines, et al, 1975, found a rapid increase in the percent of 'No Response' to red light at 60° eccentricity and beyond. No departure from normal 1-5% 'No Response' occurred with blue or green light to a limit of 90°.

Utility of peripheral areas of the eye differ according to the visual task required. Edwards and Goolkasian, 1974, presented electroluminescent letter displays at 10°, 15°, 25° and 58° along the horizontal meridian and required four kinds of visual tasks: detection, recognition, identification and categorization. At any given peripheral angle, reaction time was longer and response accuracy decreased as the task was more complex. MacLeod, 1977, required choice-reaction time and letter identification tasks in response to peripherally displayed letters along eight meridians. Response time and identification accuracy did not vary with peripheral angle within 24° eccentricity along the horizontal meridians (270° and 90°). Significant differences in visual responses were found for the vertical and oblique meridians.

Comparable kinds of information about the relative usefulness of peripheral visual fields is not available for underwater viewing environments. Water

effects and suspended particle effects need to be accounted for in assessing the utility of the visual periphery for information display in underwater vehicles and other diver support systems. Vaughan, et al, 1977, simulated naturally turbid waters with selected concentrations of latex particles of known diameters and densities. They used simulations of 'Ocean' vs 'Harbor' turbidity conditions as viewing environments for assessing legibility requirements for underwater displays. Variations in turbidity accounted for large proportions of legibility responses when luminance, color, size and viewing distance were varied. In their experiments, numeric displays were presented at zero eccentricity and the observer's response was number identification.

The present study was conducted in order to extend knowledge of underwater display optimization to include peripheral visual fields and both detection and identification tasks.

II. METHOD

A. Turbid Water Simulations

Natural underwater viewing environments include suspended materials which scatter light. The effects of the scattering which are of consequence to display design are first, the reduction of brightness contrast between the lighted display and the bacground against which the display must be discriminated, and second the reduction of total light energy reaching the eye. Both of these phenomena are interactive functions of the sizes and concentrations of suspended particles, and the wavelength, size and intensity of the display. One of the main objectives of the present research was to quantitatively assess the effects of turbidity variations as determinants of display design optimization.

Two levels of natural water turbidity were represented in this experiment: one simulated ocean water, the second simulated harbor water. The two simulations considered the sizes and concentrations of naturally occurring suspensoids as reported in the literature of physical oceanography. Particle sizes were selected to represent the median value of ocean and harbor suspensoids; concentrations were selected to represent typical numbers of scatterers per cubic centimeter of water. 'Ocean' turbidity was defined by relatively large-sized suspensoids at very low concentration; 'Harbor' turbidity by very small-sized particles in relatively high concentration. Quantitatively the two simulations were defined by particle diameters and numbers of scatterers per cubic centimeter as presented in Table 1. Additional details concerning the artificial materials, and the formulas which account for density differences between the artificial particles and the naturally occurring suspensoids are reported in Vaughan, et al, 1977.

The 'Ocean' and 'Harbor' simulations were based on physical characteristics of the naturally occurring suspensoids in real-world oceans and harbors. As a test of the adequacy of the physical simulations, optical characteristics of the artificially turbid waters were measured and compared to real-world values. Furthermore, several samples of each water type were taken during the conduct

Table 1. Particle Sizes and Numbers Defining 'Ocean' and 'Harbor' Turbidity Simulations

	Particle Diameter and Standard Deviation	Number of Scatterers per cm^3
'Ocean'	$\overline{X} = 25.7 \times 10^{-6}$ m $\sigma = 10.0 \times 10^{-6}$ m	4.64×10^2
'Harbor'	$\overline{X} = 1.091 \times 10^{-6}$ m $\sigma = 0.0082 \times 10^{-6}$ m	7.20×10^6

of the experiment as a check on the relative consistency of the viewing environment used as a test medium. Also of interest was the extent to which samples of 'Harbor' and 'Ocean' waters produced for the current experiment compared to those same simulations used in experiments conducted the previous year. Optical density of the water samples according to wavelength was the characteristic by which the above comparisons were made.

Transparency of the water was measured using a Beckman model DK Spectrophotometer. This device is a common laboratory instrument used typically by chemists for the determination of absorptance of colored liquids. It has the advantages of being easy to use, only requiring a 10 ml sample, and producing a continuous output of transmittance vs wavelength throughout the entire visible spectrum. Unfortunately spectrophotometers are designed primarily for use with non-scattering fluids, so that the measured transparency of a sample containing suspended material is some undefined combination of the effects of absorption and scattering and is not directly related to the relative irradiance loss coefficient (k) or the narrow beam attenuance coefficient (α). Since it was desired to reproduce as closely as possible the transparency of natural water in these experiments, the optical measurement chosen was one that would satisfactorily compare naturally with artificially turbid water. The reported values of optical density should therefore be considered only in the context of comparing the artificial and natural waters.

Since Optical Density (OD) is defined as:

$$OD = \frac{\log\left(\frac{100}{\%T}\right)}{L}$$

where L is the path length, this OD may be converted to the OD for any path length by simply multiplying by one-tenth the desired path length in cms. Thus, if the OD for a 10 cm path is reported as 0.5, the OD for a 1 cm path length would be (0.5) (1/10) = 0.05, that for L = 30 cm would be (0.5) (30/10) = 1.5, and that for a 1 meter path would be (0.5) (100/10) = 5.0.

If it is desired to convert to a measure more comparable to the attenuation coefficients commonly used in the oceanographic literature, we note:

$$\alpha = \frac{\log_e\left(\frac{100}{\%T}\right)}{L}$$

so that we simply convert from $\log_{10}$ to $\log_e$ by multiplying by the constant 2.3:

$$\alpha = 2.3\ (OD)$$

Thus, for a reported transmittance of 80% for a 10 cm cell, we would get:

$$OD = \frac{\log (100/80)}{10} = \frac{.097}{10} = .0097\ cm^{-1} = .97 m^{-1} \quad \text{and}$$

$$\alpha = 2.3\ (OD) = .022\ cm^{-1} = 2.2 m^{-1}$$

The Spectrophotometer records transparency with respect to some standard, in this case distilled water, so that the measured optical density is descriptive of the sample material in addition to pure water and does not include the water itself. If the total optical density (OD) or attenuation coefficent (α) is desired, the additive properties of these two parameters may be used, i.e.:

$$OD_{total} = OD_{suspensoids} + OD_{water}$$

$$\alpha_{total} = \alpha_{suspensoids} + \alpha_{water}$$

Four samples of 'Ocean' water and four of 'Harbor' were taken during the conduct of the present experiment. Figure 1 shows the mean optical density values of the 'Ocean' and 'Harbor' samples. Characteristically, the optical effects of the small-sized scatterers in large numbers ('Harbor') was to reduce the transmission of light as an inverse function of wavelength. The 'Ocean' simulation of large-sized particles in small numbers produced a highly transmissive environment indifferent to wavelength. Figure 1 also includes the regression equation for optical density (y) as a function of wavelength (x).

Additional analyses of the optical density functions as well as the basic data tables are presented in Appendix A.

B. Apparatus

The artificially turbid water was contained in a 70 gallon tank of the following dimensions: Length, 91.4 cm; width, 78.7 cm; height, 55.9 cm.

Particles were kept in suspension by a pumping system. Two small submersible pumps were placed on the bottom at opposite ends of the tank. The output of each of these pumps was attached to a diffuser consisting of a piece of pipe with 1/8" holes spaced every two inches along the length. These holes were oriented so that the pump output was directed along the bottom toward the center. In this manner it was hoped that the water would be sucked in at each end of the bottom, move toward the center horizontally, rise to the surface in the tank's central region, move toward the ends at the surface then sink. This motion was designed to produce maximum turbulence in order to keep the particles in suspension.

A drywell was constructed within the tank perpendicular to the line of sight of a facemask mounted at one end of the tank. The drywell was capable of movement along the longitudinal axis of the tank and could be positioned at any distance from the faceplate between 5 and 64 cm (2 and 25 inches). This drywell-within-a-wet-tank apparatus avoided the need to waterproof experimental displays and yet required the displays to be viewed through a water column.

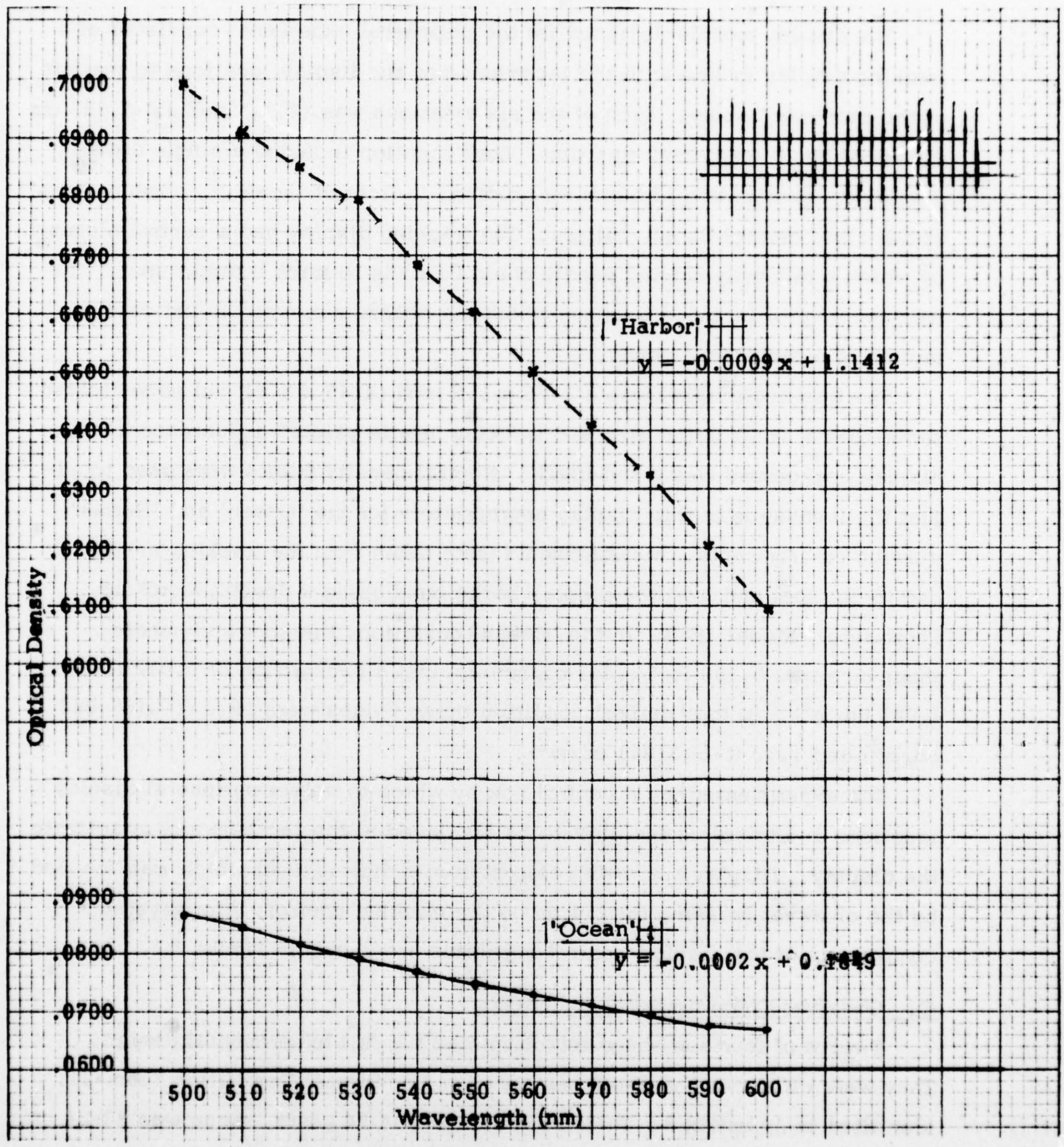

Figure 1. Optical Density per Wavelength for 'Ocean' and 'Harbor' Turbidity Simulations

The display module designed for the peripheral experiment consisted of a tracking display in line with the facemask, and six display locations to the left of the tracking display. Each of the six locations was (2.125 inches) 5.397 cm distance from the adjacent position. Each location included a single digit display and a mounting platform for holding, in front of the digit, combinations of color and neutral density filters. The tracking display had a control element by which a randomly moving needle could be made to track a target spot. The tracking control included a button which the observer pressed to indicate detection of a peripheral signal.

The tracking display was a 1.75 x 1.5 inch (4.45 x 3.81 cm) edge-lighted meter with a small target spot and tracking needle painted a fluorescent white; display background was a flat black. Neutral density filters were used to adjust the luminance of this display appropriately for the 'Ocean' and 'Harbor' viewing environments. Measurements were taken from the tracking needle and target spot and from the display background using a Spectra Pritchard Photometer, Model 1980. In the 'Ocean' condition, the spot and needle luminance was 0.190 ft-L (.651 cd/m^2) against a background of 0.012 ft-L (.041 cd/m^2). In the 'Harbor' condition these values were 19.0 ft-L (65.094 cd/m^2) and 1.15 ft-L (3.941 cd/m^2).

The experimenter had a control box by which to select peripheral display locations 1-6, to select the digit to be displayed at the location and to activate the display. Display activation also started a digital timer which was stopped by the observer pressing the button on the tracking control. The several components of the display/control apparatus are shown in Figure 2.

C. Observer Characteristics and Tasks

Twelve of fourteen observers completed the full experimental design. They were officer and enlisted personnel of Underwater Demolition Team-21, identified in Appendix B. Their average age was 24 years, range was 20-34 years. All had normal color vision and 20/20 near acuity. Their average accommodation near-point was 12.6 cm, range was 9-17 cm.

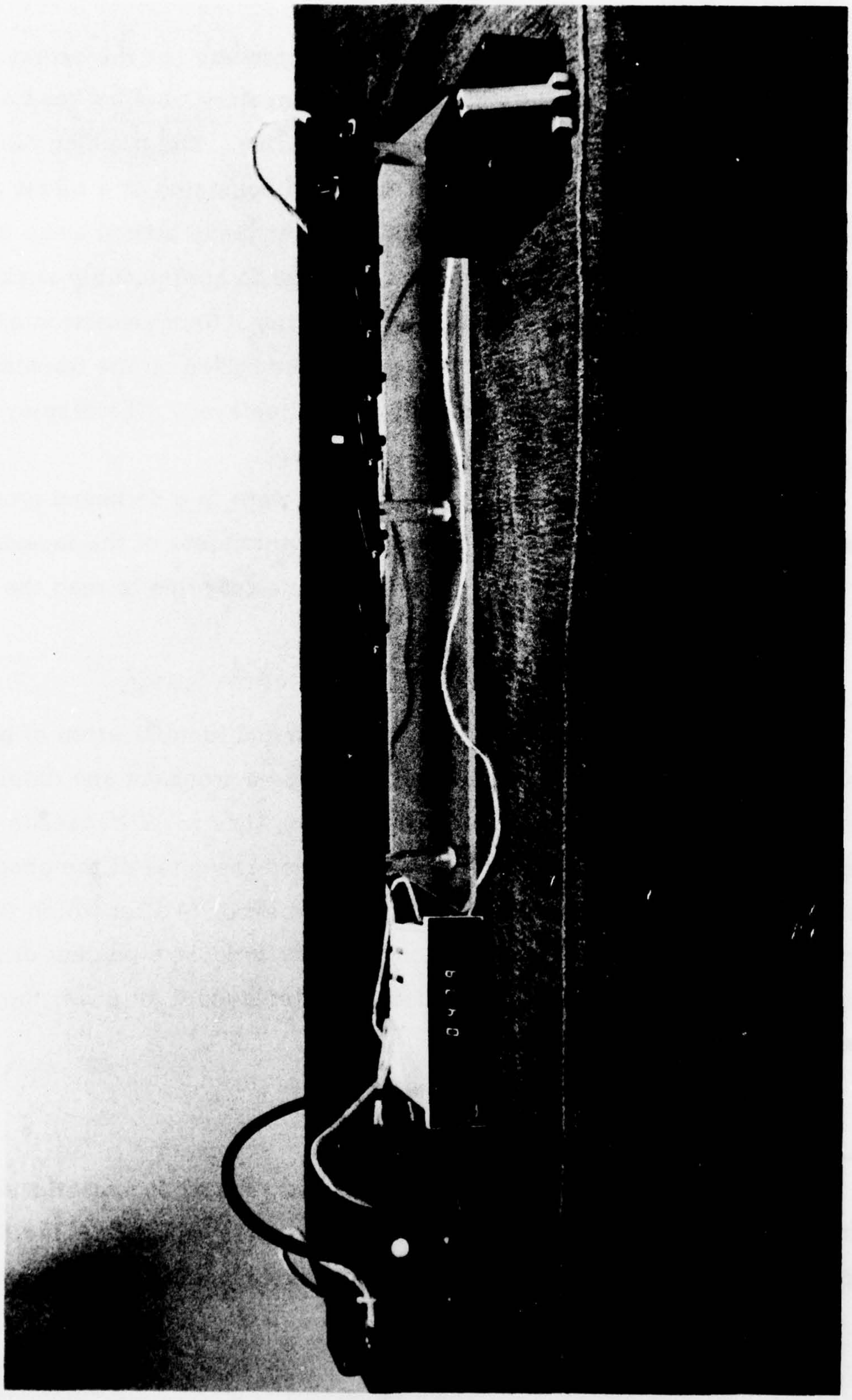

Figure 2. Apparatus Used in the Experiment

Their task was abstracted from those characteristic of the operator of a submersible vehicle. They attended to a compensatory tracking task as in holding a compass needle to a prescribed heading. The tracking display was directly in the center of the visual field and consisted of a target dot and a controllable pointer, which continuously and randomly drifted away from the target. The tracking control enabled the observer to continuously work at the error-nulling task typical of compensatory tracking. Upon detection of a peripheral light stimulus the observer pressed the button on the tracking control, then attempted to identify the digit being displayed. The display was turned off after three seconds.

The observers were dark adapted; all trials were in a darkened room. The observer's head was fixed by the location and constraints of the facemask; he was instructed to use maximum eye movement in attempting to read the peripherally displayed digit.

D. Dependent Variables

The performances of interest were detection and identification of peripheral displays under the several conditions of viewing environment and display characteristics. Detection was measured by reaction time in milliseconds from onset of the peripheral display to the button press response of the observer. Response times were recorded to a limit of three seconds after which time 'No Response' was recorded. Identification was measured as a percent of the twelve observers who correctly identified the displayed digit under the given experimental conditions.

No data were recorded from the tracking task.

E. Display Variations

The basic light source was a seven-segment, incandescent-filament, digital display commercially available as Pinlite DIP 640 from Refac Electronics Corporation. The height x width dimensions were 8 x 4 mm. The individual

filament segments averaged 2300 ft-L (7980 cd/m^2) in luminance when measurements were taken from the center of the filament with a photopically calibrated Spectra Pritchard Photometer, Model 1980, using an MS-80 lens and a 6-minute spot.

1. Color

Variations in display color were produced by placing wavelength-selective filters in front of the basic display. Two colors were used, red and green, corresponding to Kodak Wratten filters #26 and #65.

2. Luminance

Levels of display luminance were selected independently for each of the two turbidity conditions. Superthreshold values were chosen based on the previous study of display legibility for comparable wavelengths (Vaughan, et al, 1977). A display luminance of 100 ft-L (343 cd/m^2) was selected for the 'Harbor' turbidity condition and 0.1 ft-L (.343 cd/m^2) for 'Ocean'. Green and red display colors were made equivalent in luminance by use of appropriate combinations of neutral density filters. As a test for potential effects of luminance on peripheral visual performance each of the superthreshold levels was reduced by 1/2 log unit, i.e., 30 ft-L (102.78 cd/m^2) for the 'Harbor' viewing environment and 0.03 ft-L (.103 cd/m^2) for the 'Ocean'.

In order to control total light energy emitted per trial, the selection of digits to be displayed was restricted to those made up of five segments, i.e., 2, 3, 5, 6 and 9.

3. Console Distance

Eye-to-console distance was varied at three levels: 25, 35 and 45 cm. Twenty-five centimeters was chosen as an inner boundary condition for long-duration performance of visual tasks characteristic of submersible operations. (The range of accommodation limits among the UDT personnel tested has been between 9 and 20 centimeters.) The outer boundary of 45 cm console distance was based on the threshold data of the previous experiments for the selected display luminances.

Since the physical dimensions of the basic display were not modified, display size was confounded with viewing distance as a determinant of peripheral task performance. As console distance increased from 25 to 35 to 45 cm, size, in terms of visual angle of the display at the eye, decreased from 110' to 78' to 61' of arc (based on the 8 mm height dimension). Any performance effects of viewing distance are, therefore, attributable to a distance/size interaction.

4. Peripheral Angle

Since the locations of the six peripherally placed digits were fixed distances from the tracking display, the peripheral angle of each location varied as console distance was varied. Therefore, the six peripheral locations could be compared only within the console distances. However, four peripheral angles occurred at each of the three console distances which were within a few degrees of each other. These four angles were defined by their mean values and used in analyses across console distances. Table 2 presents these selected angle-by-console distance combinations.

As is the case for operational display consoles in submersible vehicles, the experimental 'console' face was a flat surface and not a concave arc. Therefore, unlike classical perimetry, the light path from the display to the eye lengthened with increased peripheral angle at any given console distance.

Table 2. Four Peripheral Angles Compared Across Console Distances

Console Distance			
25 cm	35 cm	45 cm	$\overline{X}$
12°	9°	7°	9°
23°	25°	26°	25°
33°	32°	33°	33°
41°	40°	40°	40°

The complete set of angular and linear data characterizing the six peripheral display locations relative to the eye is shown in Table 3.

F. Experimental Design and Procedure

The experiment was conducted as a 6 x 2 x 3 x 2 factorial design with one nested variable; two levels of display luminance were nested within one level of console distance. The design was first implemented with the 'Ocean' turbidity condition, then repeated with the 'Harbor' viewing environment. Any practice effects, therefore, will benefit the more difficult conditions rather than spuriously creating poorer performances. Since each of the twelve observers contributed data to each cell of the design in both the 'Ocean' and 'Harbor' conditions, individual differences do not contribute to error terms in the analysis of variance. Table 4 is an outline of the design as applied to both 'Ocean' and 'Harbor' underwater viewing environments.

The twelve observers were assigned to trial sequences so as to balance order effects of display color and console distance. Within a block of trials defined by a Display Color and a Console Distance, peripheral locations, digits presented and stimulus onset delay times were independently randomized for each observer. Overall, the design was modeled after repeated measurements designs as described by Weiner, 1962, and by Myers, 1972.

Procedurally the observer was shown the apparatus and briefed about the purpose of the experiment and about the tasks he was to perform. Then the observer was screened for visual requirements: normal color vision (American Optical Corporation's Pseudo-Isochromatic Color Plates), 20/20 near acuity and accommodation near-point less than 25 cm. With the test room at high ambient luminance, the observer was given 12 practice trials (two at each of the six peripheral locations). Observers tended to work the tracking control with their preferred hand and to press the timer-stopping button with the index finger.

Table 3. Angle and Distance Relationships Among the Six Peripheral Display Locations At the Three Console Distances

Display Position	Lateral Distance of Display from Line-of-Sight		At 25 cm Console Distance		At 35 cm Console Distance		At 45 cm Console Distance	
	(Inches)	(cm)	Peripheral Angle (°)	Slant Range (cm)	Peripheral Angle (°)	Slant Range (cm)	Peripheral Angle (°)	Slant Range (cm)
1	2.125	5.3975	12°	25.576	9°	36.050	7°	45.890
2	4.250	10.7950	23°	27.231	17°	37.116	14°	46.770
3	6.375	16.1925	33°	30.240	25°	39.238	20°	48.311
4	8.500	21.5900	41°	33.487	32°	41.598	26°	50.393
5	11.625	29.5275	50°	39.120	40°	46.294	33°	54.289
6	14.750	37.4650	56°	45.472	47°	51.720	40°	59.016

Table 4. Experimental Design Outline

Peripheral Location	Green Display: Console Distance (cm)/ Display Luminance (1 & 2)				Red Display: Console Distance (cm)/ Display Luminance (1 & 2)			
	25/L1	35/L1	35/L2	45/L1	25/L1	35/L1	35/L2	45/L1
1								
2								
3								
4								
5								
6								

The test room was made dark and observer was dark adapted 20 minutes, during which time the procedures were verbally rehearsed. An additional six practice trials were run following dark adaptation according to the following steps.

- Experimenter sets up condition of trial and says 'Ready'.
- Observer places face in facemask and begins the compensatory tracking task.
- Experimenter delays 2-8 counts and initiates peripheral display.
- Observer stops timer and reports which digit he saw or that he could not identify the digit.
- Experimenter records reaction time and digit named.
- Observer withdraws face from mask and waits for next trial.

G. Summary of the Experimental Conditions

An overview of the variables included in the present experiment is presented in Table 5.

Table 5. Organization of the Variables Included in the Experiment

Observer Characteristics	Visual Tasks Required	Variations in the Viewing Environment	Variations in Display Characteristics
Normal color vision 20/20 near acuity Accommodation near-point < 17 cm Dark-adapted Binocular viewing through a full facemask with 14.29 cm (5.625") wide faceplate Head fixed, eyes free for maximum movement	Detect onset of a peripherally displayed light signal Identify the value of the peripherally displayed digit (2, 3, 5, 6 or 9) Continuous compensatory tracking task with line-of-sight display	'Ocean' turbidity simulated with 25 micrometer diameter particles 'Harbor' turbidity simulated with 1 micrometer diameter particles	Console distance: 25, 35 and 45 cm Display Color: Red and Green Display Luminance: 100 and 30 ft-L in the 'Harbor' water at 35 cm .1 and .03 ft-L in the 'Ocean' water at 35 cm Peripheral Angle: 6 angles within a given console distance 4 angles across console distances

III. RESULTS

A. Detection of A Peripheral Display*

1. Peripheral Detection in An 'Ocean' Viewing Environment

Two analyses were made of the reaction time data: one for the condition of high (0.1 ft-L) display luminance across variations in peripheral angle, console distance and display color; a second for the condition within the 35 cm console distance and across variations in peripheral angle, display luminance and color. Table 6 presents analysis of variance summary tables for these two conditions. A 1% level of risk was selected as a criterion defining "significance" of a given effect; and an estimate of proportion-of-response variance-accounted-for, $\hat{\omega}^2$, was computed for each significant effect (Hays, 1973). These statistical steps were taken as compensations for the efficiency of repeated measures designs in detecting small differences as significant.

Table 6 suggests Display Color as a significant factor in detecting peripheral signals in an 'Ocean' environment. At high luminance (0.1 ft-L), reaction time to a red signal was consistently slower than to a green at comparable peripheral angles. Figure 3 is a plot of the reaction time data describing this effect. Between 9 and 33 degrees peripheral angle, the reaction time to a red light was about 50 msec slower than to a green light. At 40°, this difference doubled to 100 msec (1/10 of a second), but neither angle nor the Angle x Color interaction was significant and the main effect of Color accounted for only 10% of the total response variance. Even at low display luminance (0.03 ft-L) the effects, though statistically significant, were of small practical consequence. The ANOVA table shows Color, Luminance and the Color x Luminance interaction accounting for 25% of the total response variance. The magnitude of the differences, however, was on the order of 200 msec as can

*Reaction Time data tables are presented in Appendix C

Table 6. ANOVA Summary Tables for Detection Differences in 'Ocean' Turbidity

A. 0.1 ft-L Display: 4 Peripheral Angles, 3 Console Distances and 2 Colors

Source	df (Source, Error)	MS_s/MS_e	F	p	$\hat{\omega}^2$
Angle	3, 33	22291/4825	4.62	N.S.	-
Distance	2, 22	38533/9898	3.89	N.S.	-
Color	1, 11	283191/12223	23.17	< .001	.10
A x D	6, 66	5981/2650	2.26	N.S.	-
A x C	3, 33	10307/4960	2.08	N.S.	-
D x C	2, 22	5674/3788	1.50	N.S.	-

B. Within the 35 cm Console Distance: 6 Peripheral Angles, 2 Colors and 2 Levels of Display Luminance

Source	df (Source, Error)	MS_s/MS_e	F	p	$\hat{\omega}^2$
Angle	5, 55	120917/7334	16.49	< .001	.08
Luminance	1, 11	386101/32758	11.79	< .01	.05
Color	1, 11	1245174/37597	33.12	< .001	.17
A x L	5, 55	14189/6280	2.28	N.S.	-
A x C	5, 55	26999/9019	2.99	N.S.	-
L x C	1, 11	256984/19254	13.35	< .01	.03

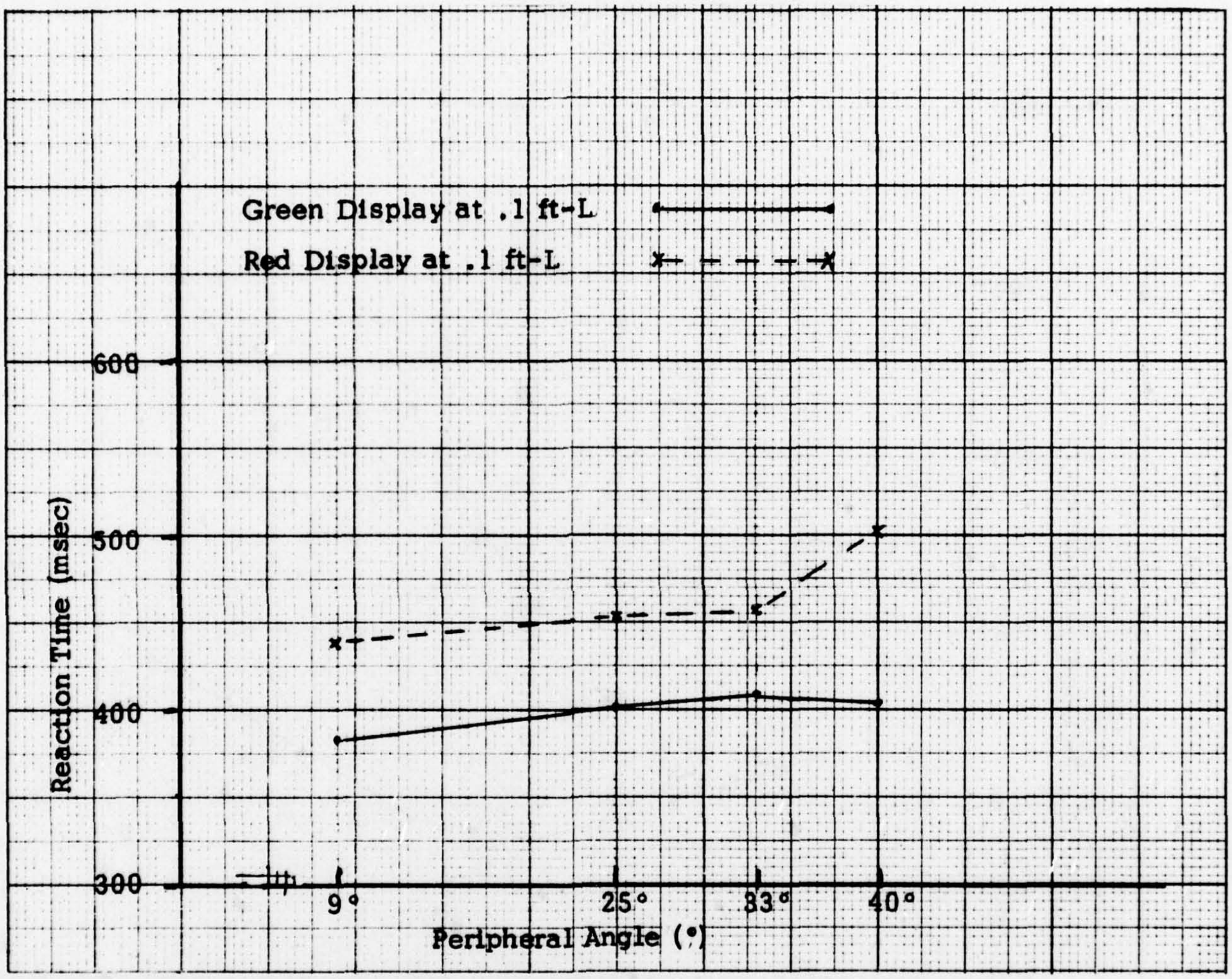

Figure 3. Effects of Color on Detection of A Peripheral Display: 'Ocean' Turbidity

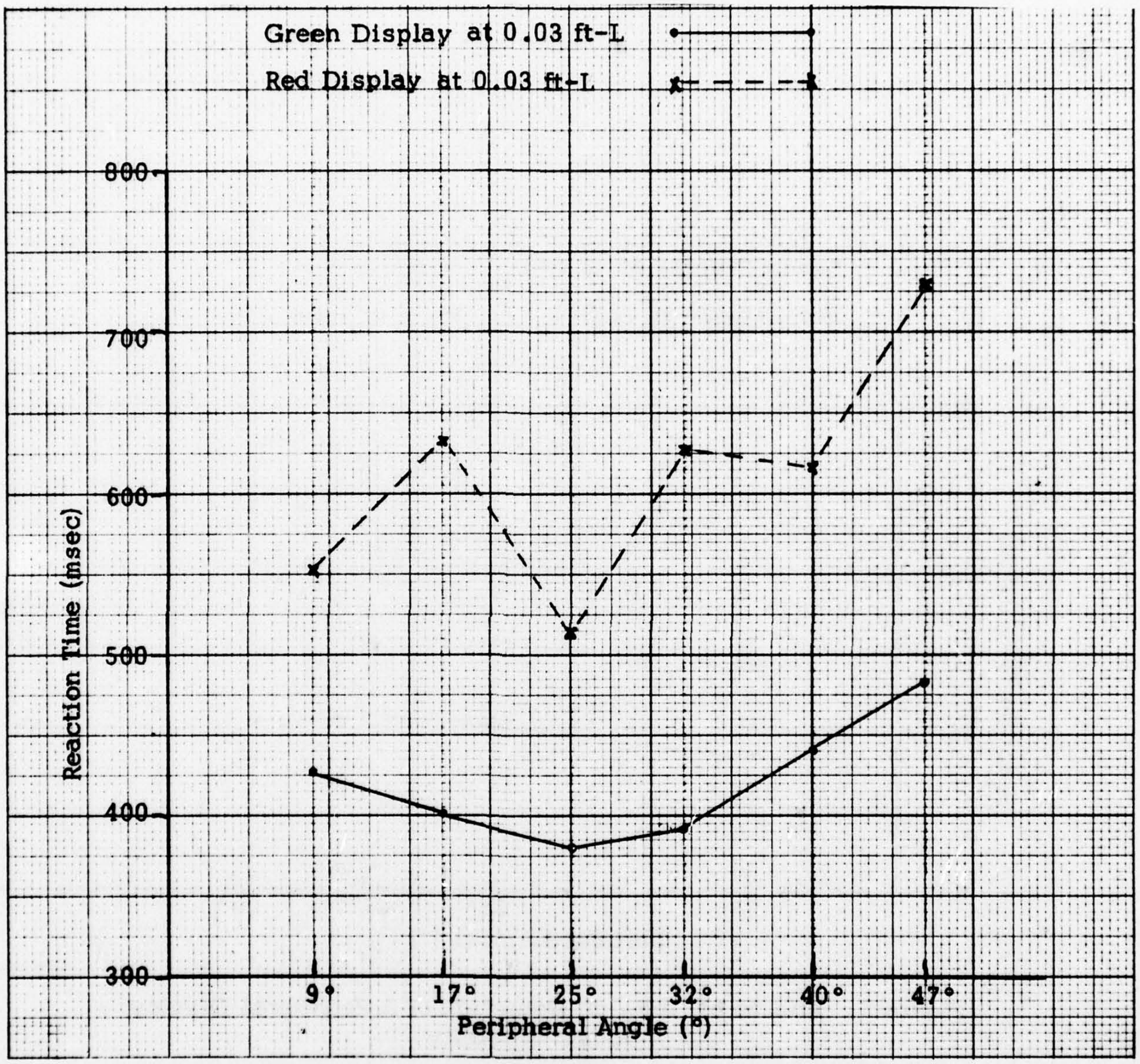

Figure 4. Effects of Color at Low Luminance on Detection of A Peripheral Display: 'Ocean' Turbidity

be seen in Figure 4. Of theoretical interest is the occurrence of reaction time minima for both Red and Green peripheral signals at 25° eccentricity; a result in general accord with data reported by Rains (1963) and accounted for by the density distribution of rod receptors across the retina.

2. Peripheral Detection in A 'Harbor' Viewing Environment

The analyses of the reaction time data in the 'Harbor' followed the identical format of the 'Ocean' data analyses. Summary ANOVA tables are presented as Table 7. Tests of each main effect and interaction were all significant beyond a reasonable risk. Hays' statistic, $\hat{\omega}^2$, was used as a basis for highlighting the factors accounting for the majority of the response variance: Console Distance and Color where display luminance was held constant; Color and Luminance where console distance was a constant. When a 100 ft-L signal was used, variations in Color, Distance and the C x D interaction accounted for 61% of the total variance in the reaction time data. Similarly, when display luminance variations were included at the 35 cm console distance, Color, Luminance and the C x L interaction accounted for 62% of the total variance.

Figure 5 illustrates both the effects of variation in display color and of the Color-by-Angle interaction. The red display consistently was responded to more slowly than the green; and the difference in reaction time between the two colors increased as peripheral angle increased.

Figure 6 illustrates both the effects of Console Distance and the Distance-by-Angle interaction. Reaction time was slower as Console Distance increased and the magnitude of the difference increased as peripheral angle increased.

Figure 7 shows the triple interaction of Color x Console Distance x Angle which suggests the main contributors to significant effects on reaction time as red display at far console distances and at wide peripheral angles.

Where display luminance was varied to include a 30 ft-L condition, the red display color was off scale beyond 17° peripheral angle at the 35 cm console

Table 7. ANOVA Summary Tables for Detection Differences in 'Harbor' Turbidity

A. 100 ft-L Display: 4 Peripheral Angles, 3 Console Distances and 2 Colors

Source	df (Source, Error)	MS_s / MS_e	F	p	$\hat{\omega}^2$
Angle	3, 33	336461/7457	45.12	< .001	.06
Distance	2, 22	1881600/11091	169.65	< .001	.24
Color	1, 11	3557778/30207	117.78	< .001	.23
A x D	6, 66	100776/6255	16.11	< .001	.04
A x C	3, 33	180298/5778	31.20	< .001	.03
D x C	2, 22	1063308/15339	69.32	< .001	.14

B. Within the 35 cm Console Distance: 6 Peripheral Angles, 2 Colors and 2 Levels of Display Luminance

Source	df (Source, Error)	MS_s / MS_e	F	p	$\hat{\omega}^2$
Angle	5, 55	445499/8003	55.67	< .001	.11
Luminance	1, 11	2210603/12187	181.39	< .001	.11
Color	1, 11	9549390/45179	211.37	< .001	.46
A x L	5, 55	89312/8731	10.23	< .001	.02
A x C	5, 55	201036/9504	21.15	< .001	.05
L x C	1, 11	1043773/21347	48.90	< .001	.05

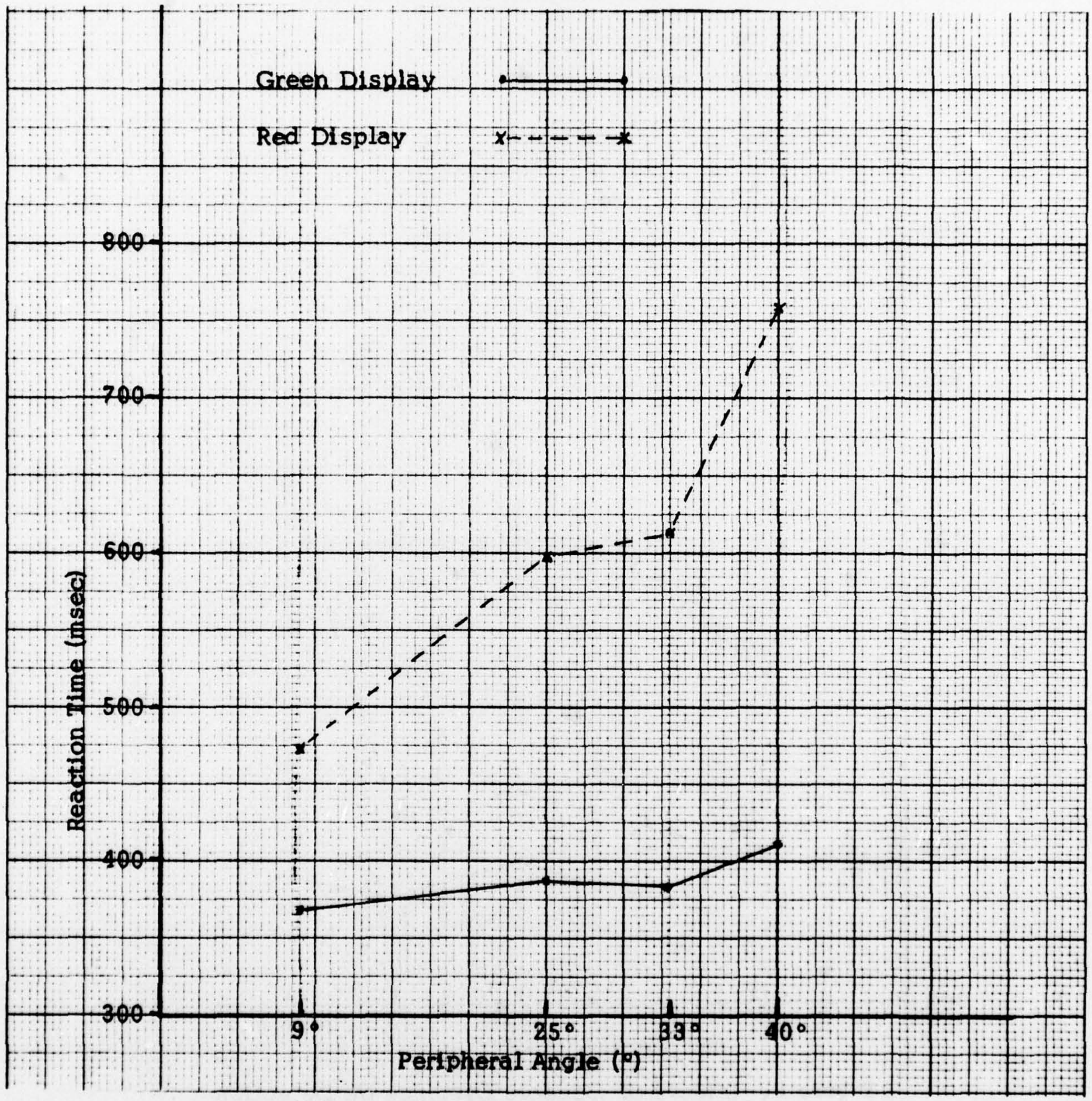

Figure 5. Effects of Color on Detection of A Peripheral Display: 'Harbor' Turbidity

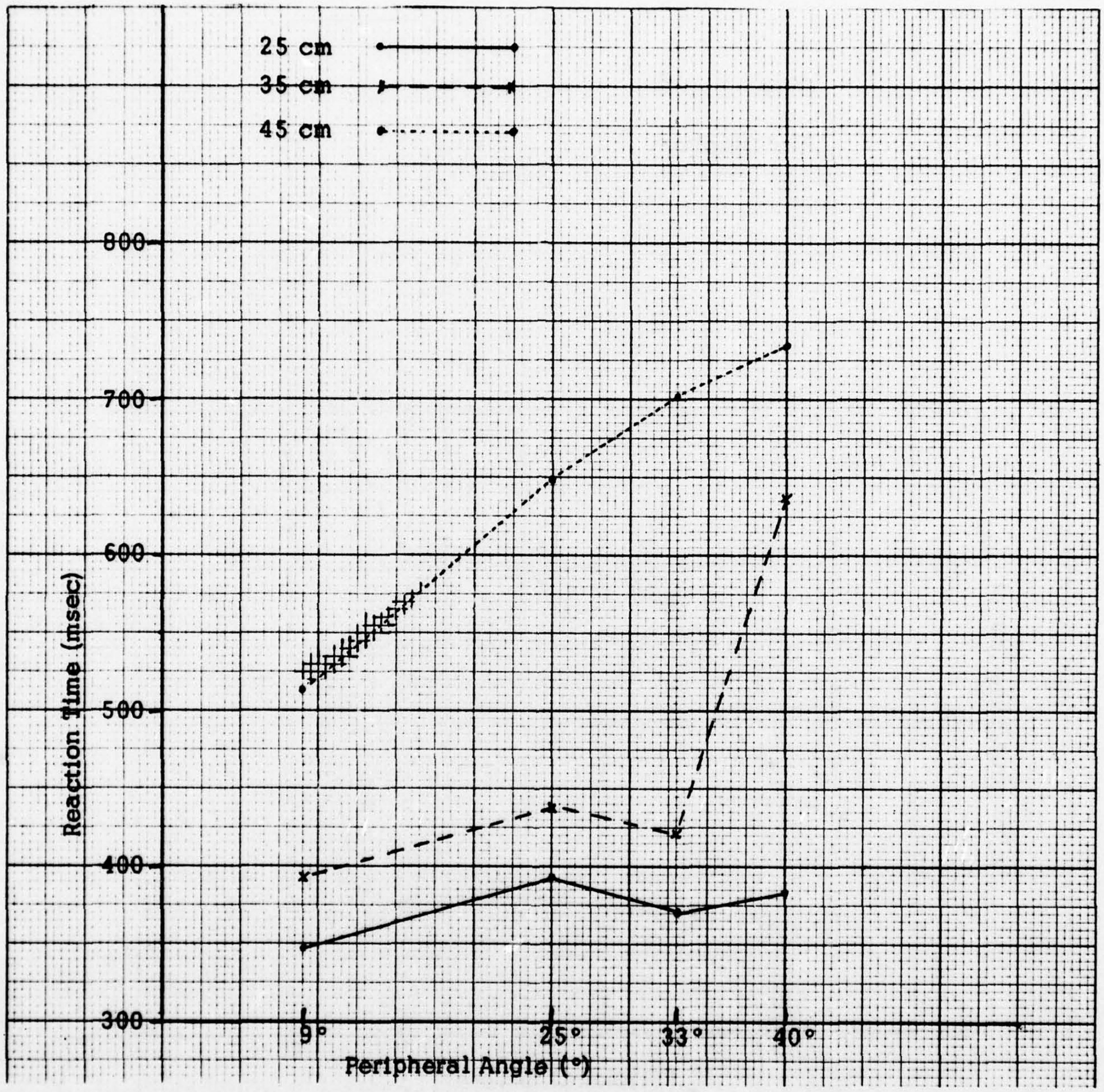

Figure 6. Effects of Console Distance on Detection of A Peripheral Display: 'Harbor' Turbidity

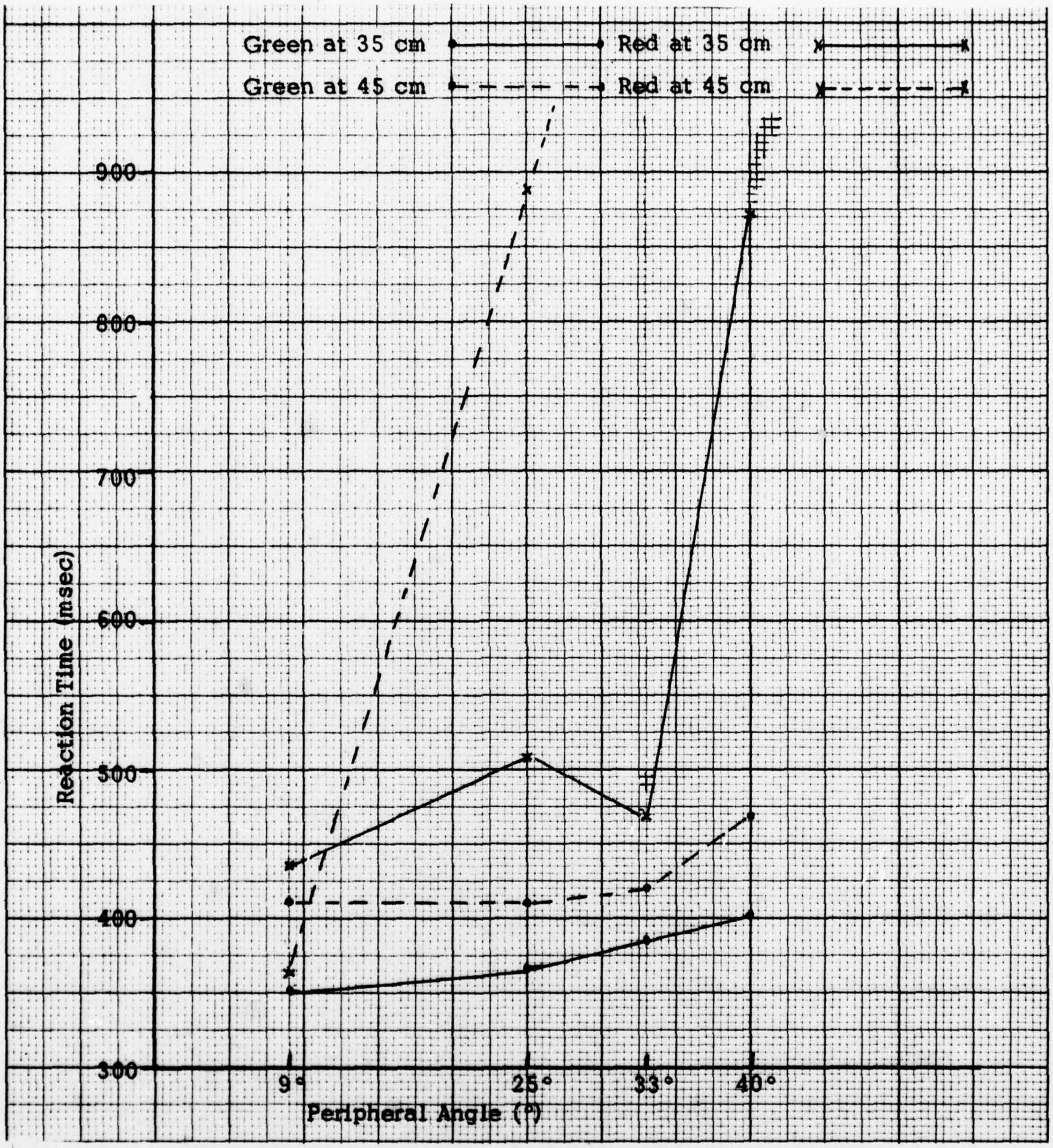

Figure 7. Effects of the Color x Distance Interaction on Detection of A Peripheral Display: 'Harbor' Turbidity

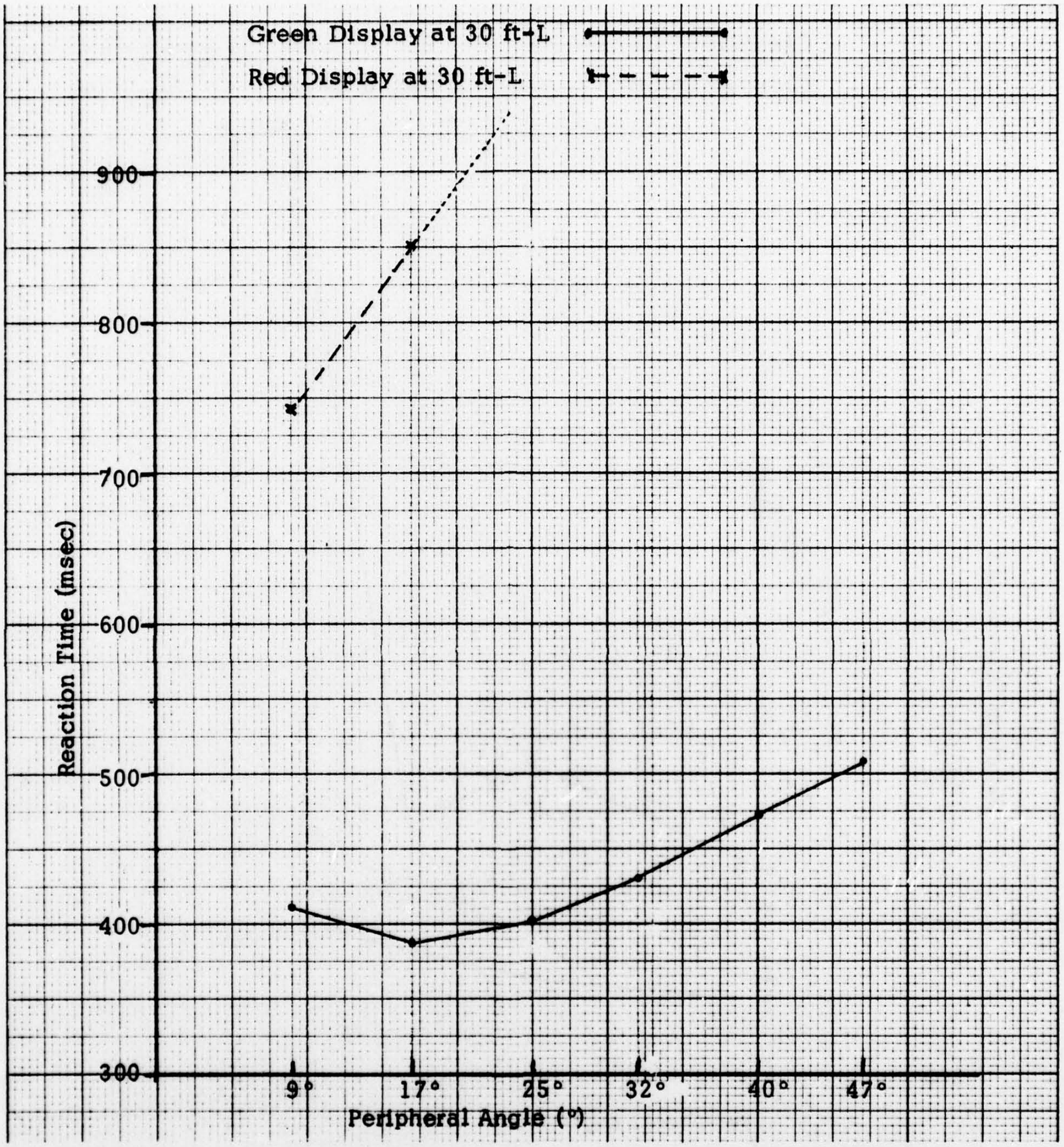

Figure 8. Effects of Color at Low Luminance on Detection of A Peripheral Display: 'Harbor' Turbidity

distance. Reaction time to the green display under these same conditions was relatively uneffected by the 1/2 log reduction in display luminance. Figure 8 shows the data for the low display luminance condition.

3. <u>'No Response' Data for the 'Ocean' and 'Harbor' Viewing Environments</u>

A stimulus duration of three seconds (3000 msec) was the limit of the observers' exposure to the peripheral light per trial. Analysis of the reaction time data from the 'Ocean' turbidity condition showed only four of 576 trials (0.7%) as undetected within this limit and only 10 of 576 trials (1.7%) as detected in excess of one second (1000 msec). All data entries of 'No Response' and those reaction times in excess of 1000 msec were included in the variance analyses as scores of 1000 msec.

The frequency of 'No Response' and of those detections in excess of 1000 msec in the 'Harbor' turbidity condition were substantially higher: 18.2% (105/576) and 4.7% (27/576) respectively. The 105 'No Response' entries were accounted for according to the data presented in Table 8. The data of Table 8 are another way of illustrating the relative effectiveness of Green <u>vs</u> Red light in peripheral detection under 'Harbor' turbidity conditions. The analysis of variance for the 'Harbor' condition included only those cells asterisked, which at the 100 ft-L level of display luminance tended to underestimate the relative advantage of Green over Red light. For example, at the most peripheral angle for each console distance (56° at 25 cm, 47° at 35 cm, and 40° at 45 cm) none of the twelve observers saw the Red light within three seconds while all of the observers detected the Green. The sensitivity of peripheral detection to the Color x Luminance interaction is also apparent in the No-Response percentages shown in Part B of Table 8.

Table 8. Percent 'No Response' to Peripheral Displays in Harbor Turbidity (N = 12)

A. Display Luminance of 100 ft-L

Display Location	At 25 cm		At 35 cm		At 45 cm	
	Red	Green	Red	Green	Red	Green
1	*	*	*	*	*	*
2	*	*			08	
3	*	*	*	*	25	
4	*	*	*	*	42*	*
5	33		50*	*	83*	*
6	100		100		100*	*

B. . Display Luminance of 30 ft-L

Peripheral Angle	At 35 cm	
	Red	Green
9°	8*	*
17°	17*	*
25°	42*	*
32°	67*	*
40°	100*	*
47°	100*	*

B. Identification of A Peripherally Displayed Digit*

Having detected the onset of a perpheral light, the observer's task was to identify the digit being displayed. Observer was instructed to use maximum eye movement in his attempt to read the display accurately. Responses were scored as either "correct" or "incorrect" so that the aggregate data consisted of frequencies of 'yes' vs 'no' responses distributed over discrete categories of display characteristics: colors, distances, angles, luminances. Selection of a statistical test for identifying significant effects required a compromise since no test was completely appropriate to these data. The basic problem was that comparisons of interest require the use of data taken from the same observers. While this is an efficient procedure for the experimental design and parametric tests of the reaction time data, no non-parametric analysis model is entirely appropriate to a repeated measures design with multiple categories of effects, i.e., 2 x k data tables (Siegel, 1956). The choice was between doing hundreds of two cell comparisons using a test of differences between correlated proportions, vs making a few tests of 2 x k and r x k tables for independent samples, i.e., the Chi Square test. The Chi Square test alternative was chosen since the consequence was to reduce the chances of reporting a significant effect where none exists. Statistically, the effect was to reduce errors of Type I in two ways: first, the multiple comparisons possible with the Chi Square test reduced the number of tests to be made; second, the effect of correlation between the sets of frequency distributions tested enlarged the error term of the Chi Square test and made the detection of a significant difference more stringent. (For elaboration regarding the effects of correlation on the Chi Square test see Edwards, 1950, p. 91.)

*Tables of identification error data are presented in Appendix D.

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1. Peripheral Identification in An 'Ocean' Viewing Environment

Table 9 is a summary of the significance tests made in the 'Ocean' turbidity condition. When the high luminance display was the stimulus, Console Distance and peripheral Angle had significant effects on identification accuracy. With distance held constant at 35 cm and display luminance varied, only Angle was a significant factor. These relationships are shown in Figures 9 and 10. Figure 9 suggests an outer limit of 33° peripheral angle for accurate identification over a range of viewing distances and Figure 10 shows accurate identification of greater than 90% to a limit of 32° peripheral angle over variations in display luminance. In the 'Ocean' viewing environment, variations in display color and luminance were not significant determinants of identification accuracy.

2. Peripheral Identification in A 'Harbor' Viewing Environment

Table 10 is a summary of the significance tests conducted for the 'Harbor' turbidity condition. At high display luminance, 100 ft-L, Console Distance and peripheral Angle were significant determiners of identification accuracy. When display luminance was reduced at the 35 cm Console Distance, both display Luminance and Color made significant differences in observers' ability to correctly identify a peripherally displayed digit.

Figure 11 shows the importance of Console Distance. At 45 cm, identification performance was inadequate at all peripheral angles; at 9° only 42% of the judgments were correct. At 35 cm console distance, identification performance was maintained at greater than 90% accuracy to a limit of 33° peripheral angle; at 25 cm, identification accuracy was 100% at 40° (but fell to 50% at 50° peripheral angle).

When display luminance was varied at 35 cm, both Color and Luminance had significant impact on accuracy of peripheral identification. These effects are illustrated in Figure 12. At 30 ft-L display luminance an identification accuracy greater than 90% was possible only at 9° peripheral angle for a Red display; the Green display was accurately identified beyond 90% to a limit of 25° peripheral angle.

Table 9. Summary of Significance Tests of Factors Affecting Peripheral Identification Accuracy in An 'Ocean' Viewing Environment

A. 0.1 ft-L Display: 4 Peripheral Angles, 3 Console Distances and 2 Colors

Source	χ^2	df	p
Angle	80.930	3	< .001
Distance	12.116	2	< .01
Color	.265	1	N.S.
A x D	2.000	6	N.S.
A x C	.250	3	N.S.
D x C	.103	2	N.S.

B. Within the 35 cm Console Distance: 5 Peripheral Angles, 2 Colors and 2 Levels of Display Luminance

Source	χ^2	df	p
Angle	205.714	5	< .001
Luminance	4.288	1	N.S.
Color	.934	1	N.S.
A x L	3.717	4	N.S.
A x C	.511	4	N.S.
L x C	.138	1	N.S.

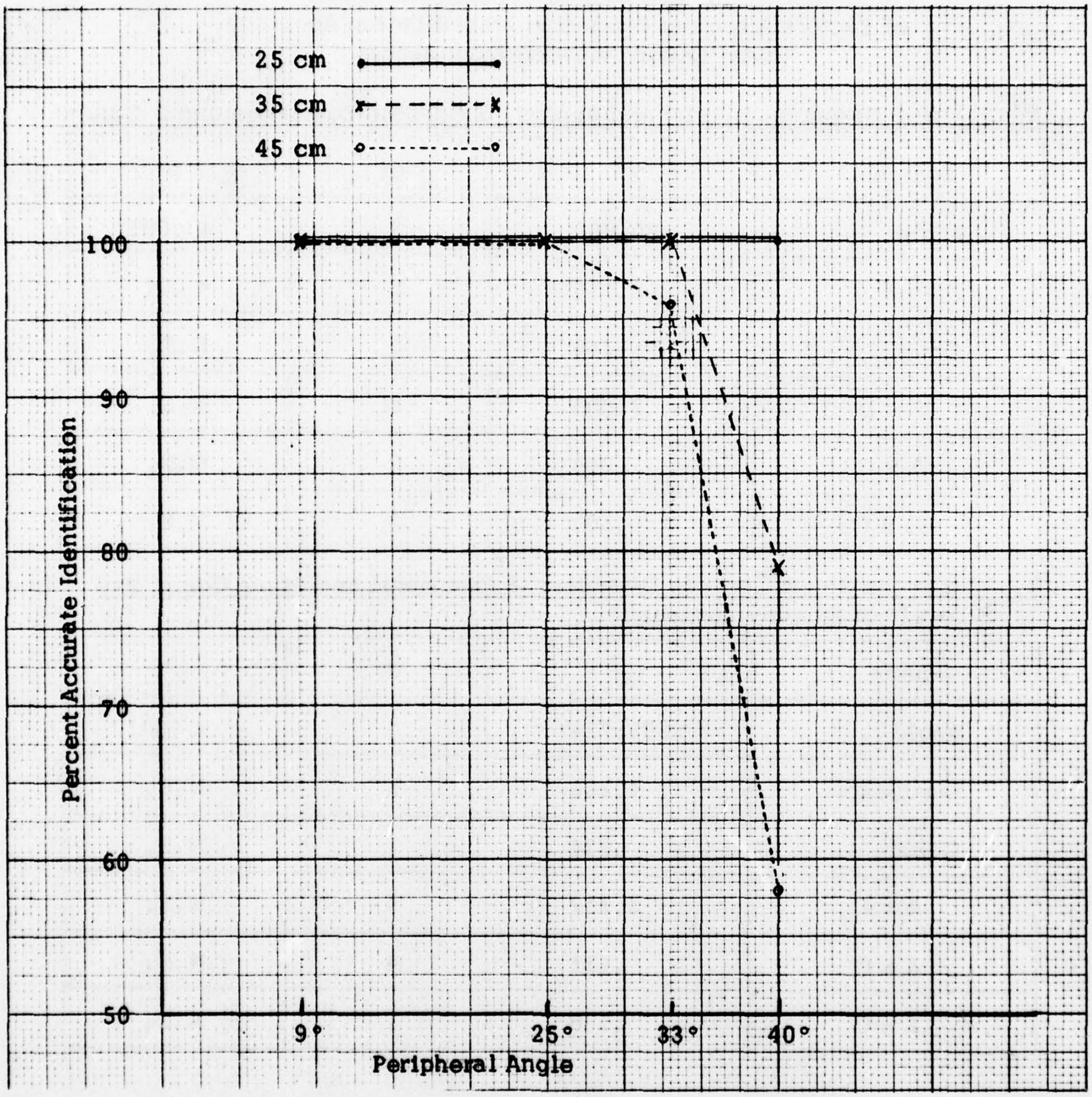

Figure 9. Effects of Console Distance on Identification of A Peripheral Display: 'Ocean' Turbidity

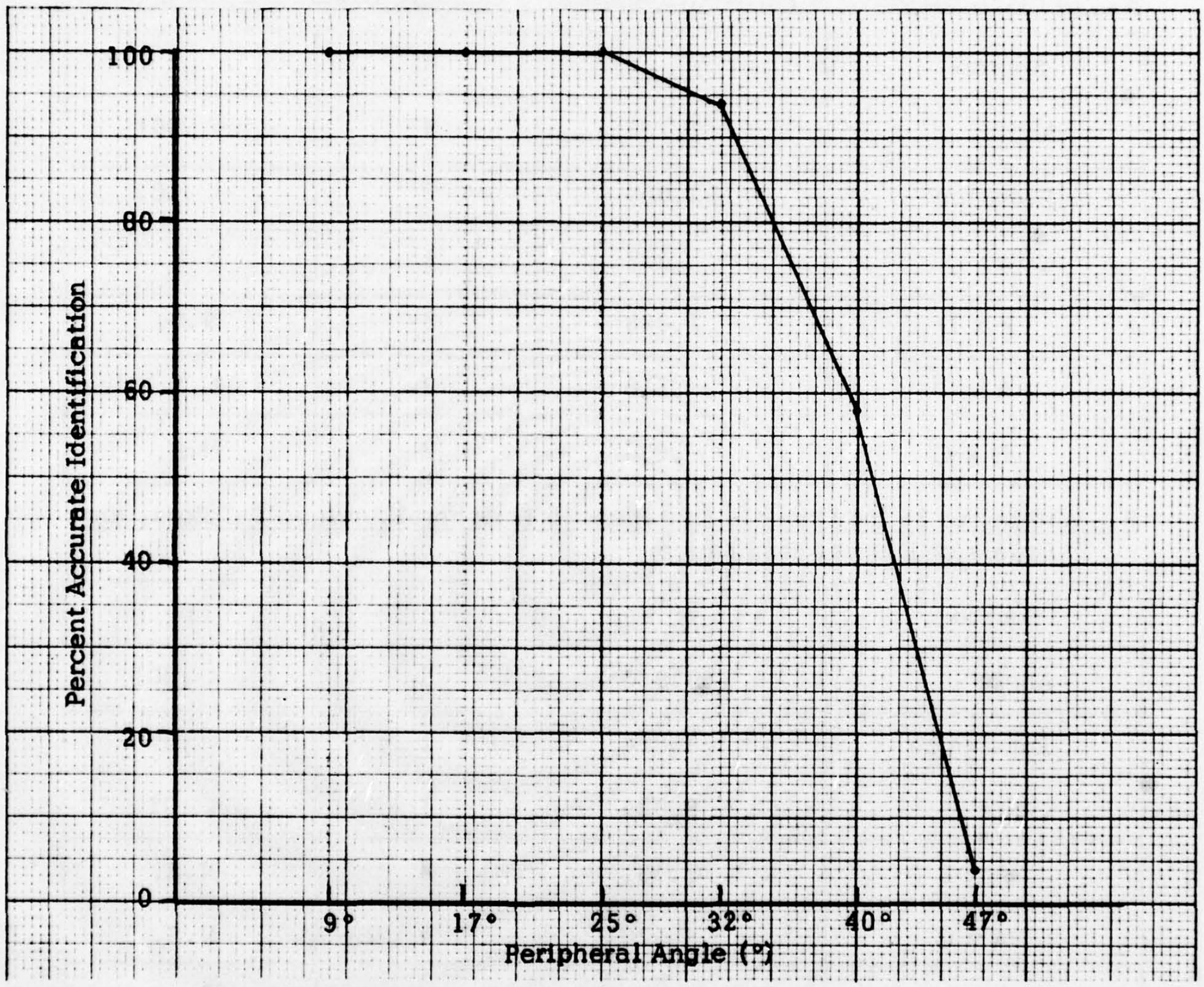

Figure 10. Effects of Peripheral Angle on the Identification of A Display: 'Ocean' Turbidity

Table 10. Summary of Significance Tests
of Factors Affecting Peripheral Identification Accuracy
in A 'Harbor' Viewing Environment

A. 100 ft-L Display: 4 Peripheral Angles, 3 Console Distances and 2 Colors

Source	χ^2	df	p
Angle	17.751	3	< .001
Distance	193.000	2	< .001
Color	.137	1	N.S.
A x D	7.328	3	N.S.
A x C	.510	3	N.S.
D x C	.690	2	N.S.

B. Within the 35 cm Console Distance: 6 Peripheral Angles, 2 Colors, and 2 Levels of Display Luminance

Source	χ^2	df	p
Angle	169.965	5	< .001
Luminance	8.824	1	< .01
Color	8.824	1	< .01
A x L	3.131	4	N.S.
A x C	4.322	4	N.S.
L x C	1.249	1	N.S.

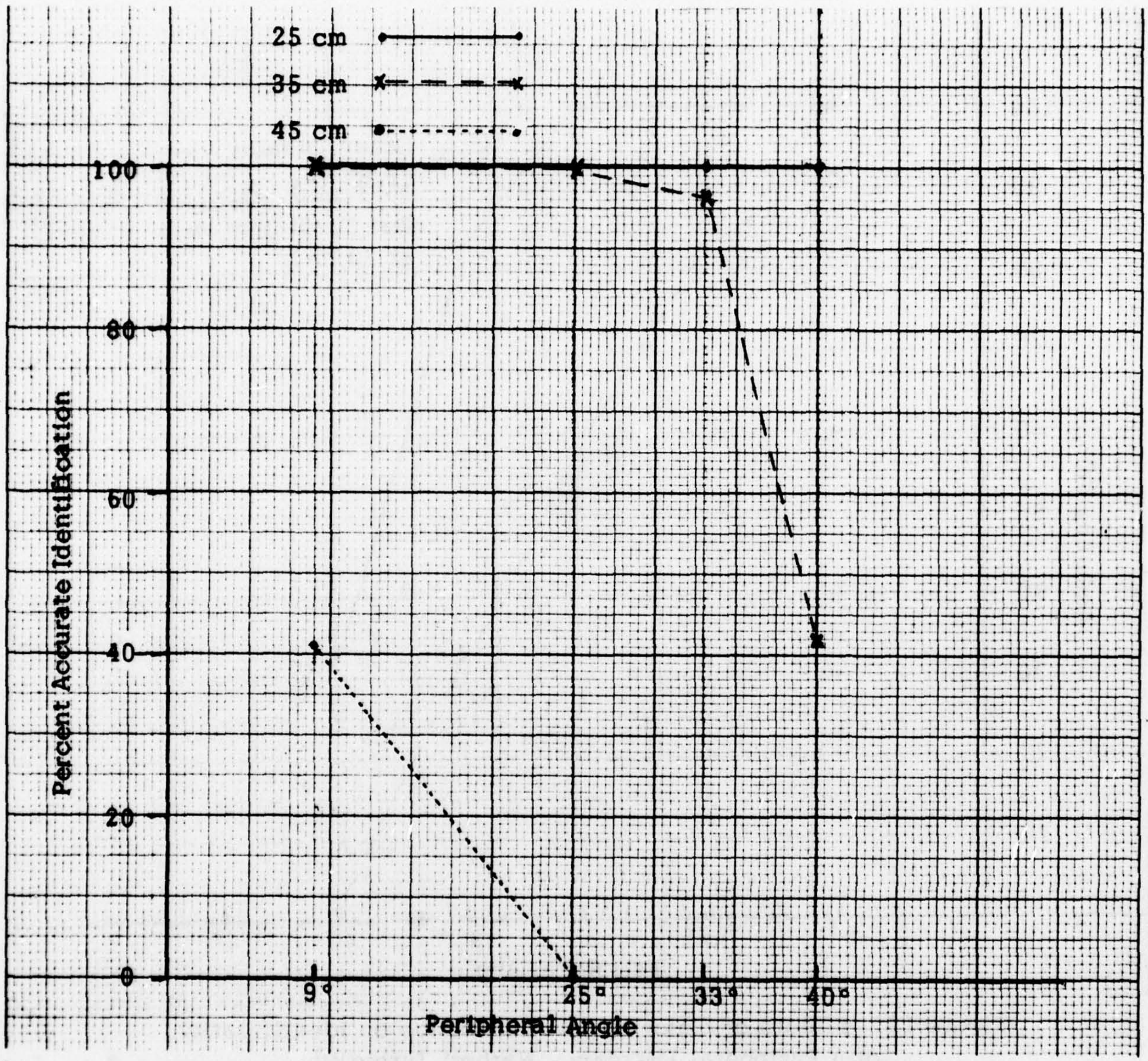

Figure 11. Effects of Console Distance on Identification of A Peripheral Display: 'Harbor' Turbidity

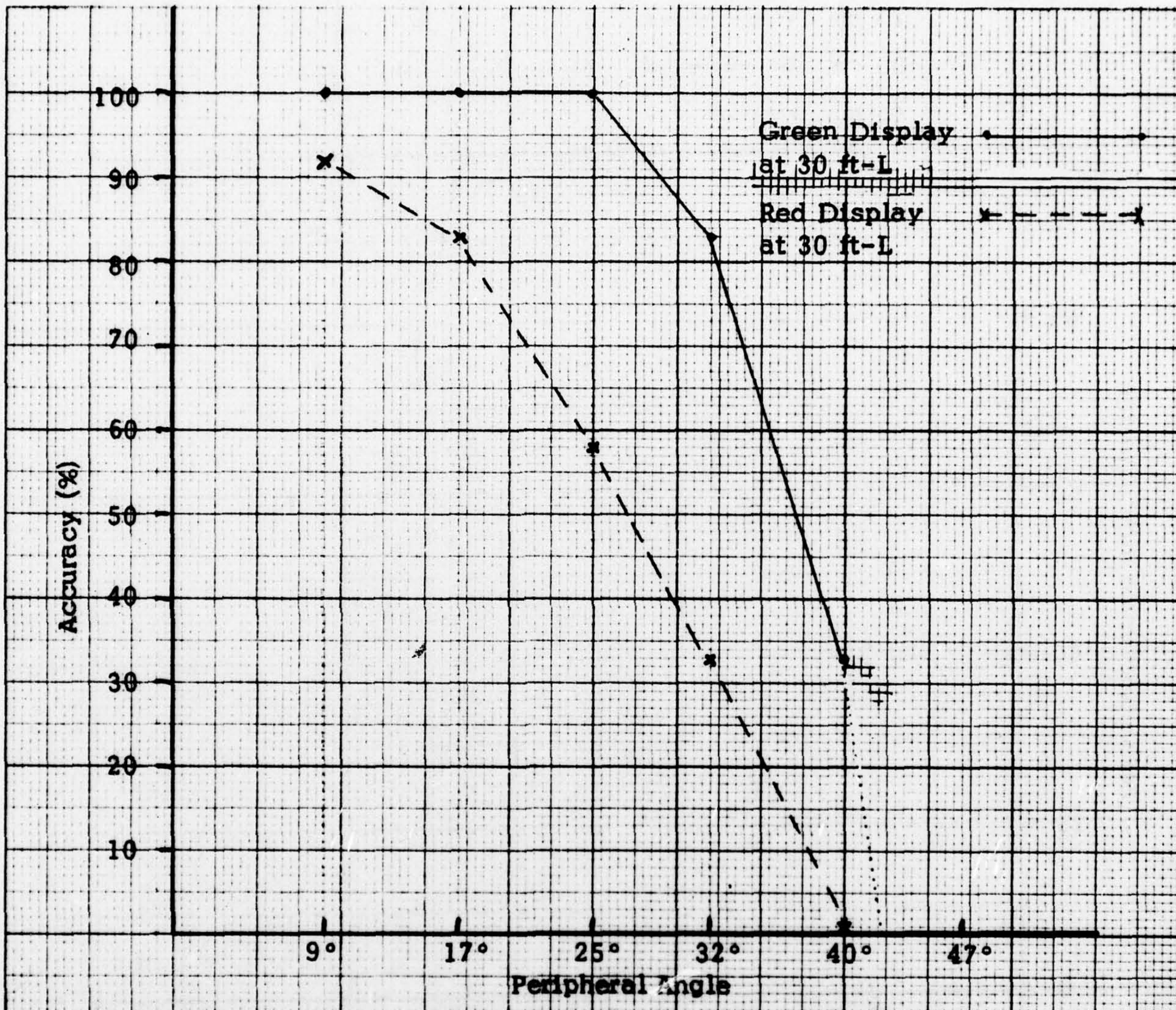

Figure 12. Effects of Color at Low Luminance on Identification of A Peripheral Display: 'Harbor' Turbidity

C. Relative Utility of the Peripheral Visual Field for Detection and Identification Tasks

1. Peripheral Detection vs Identification in an 'Ocean' Viewing Environment

Figures 13 through 16 are simultaneous plots of identification accuracy (%) and reaction time (msec) for the six peripheral angles included in the experimental trials at 35 cm Console Distance. The figures are in descending order of peripheral effectiveness for combinations of display Color and Luminance. Figures 13 and 14 show that Green light displays at either the 0.1 or 0.03 ft-L luminance adequately supported detection of peripheral signals within 500 msec to 45° peripheral angle, and identification accuracy >90% to 32° peripheral angle. All Red light displays resulted in less effective performances of the two visual tasks. Figure 15 shows that Red light at high luminance (0.1 ft-L) enabled peripheral performance of the identification task at levels comparable to Green, but detection was limited to 40° peripheral angle. Figure 16 shows the effect of a reduced luminance Red light. Identification accuracy was >90% to a limit of 25° peripheral angle and detection was longer than 500 msec at all peripheral angles.

2. Peripheral Detection vs Identification in a 'Harbor' Viewing Environment

Comparative analyses of the detection and identification functions with peripheral angle in 'Harbor' turbidity paralleled the findings for the 'Ocean' condition. Green light at high luminance (100 ft-L) was superior to all other conditions and Green light at 1/2 log lower luminance was at least as good as Red at high luminance. Red at low luminance was unable to support criterion levels of detection performance at any peripheral angle, and identification performance at any angle beyond 9°. Figures 17 through 20 illustrate these relationships.

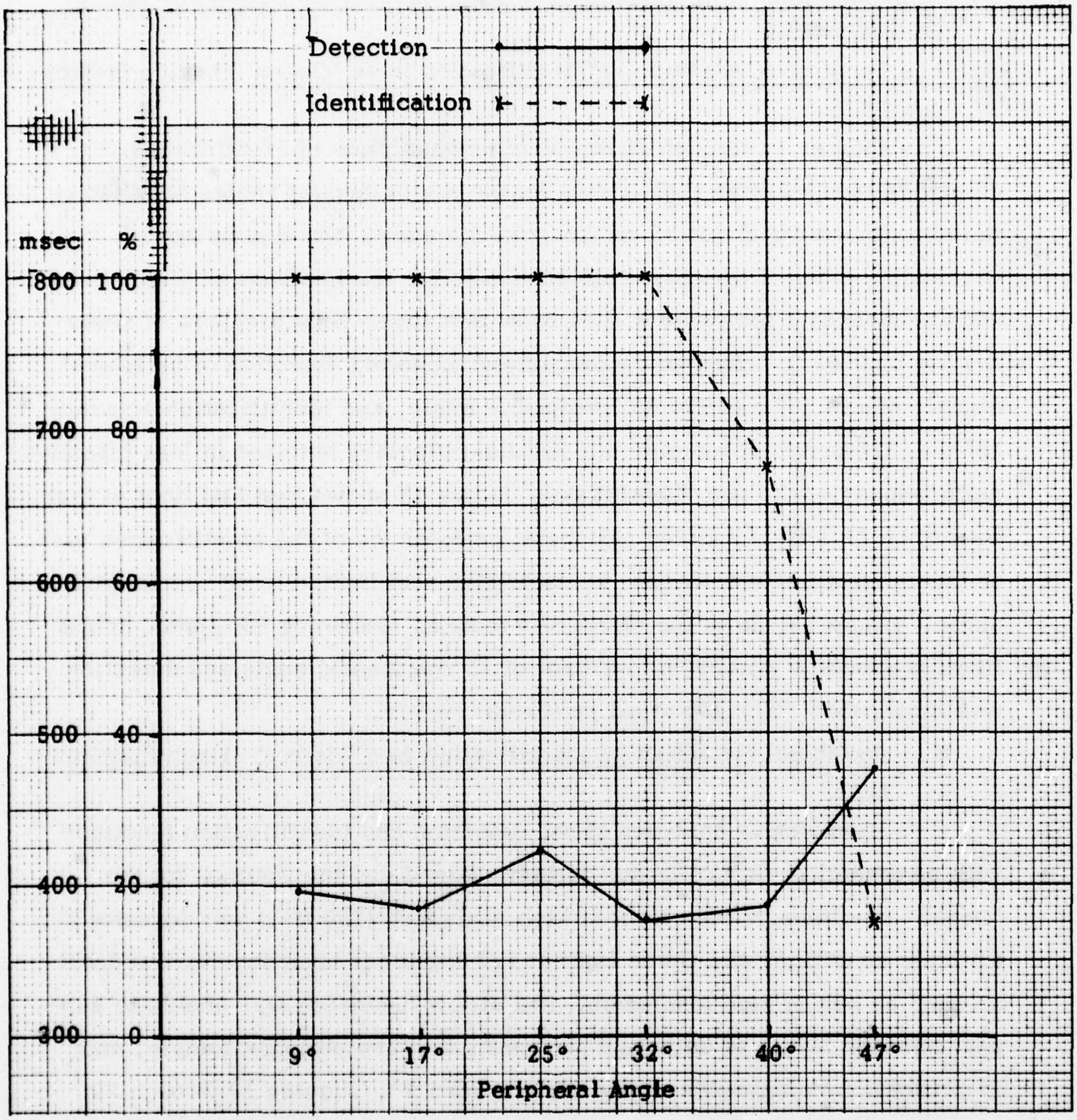

Figure 13. Detection and Identification Performance Effectiveness As A Function of Peripheral Angle in 'Ocean' Turbidity: Green Display at 0.1 ft-L

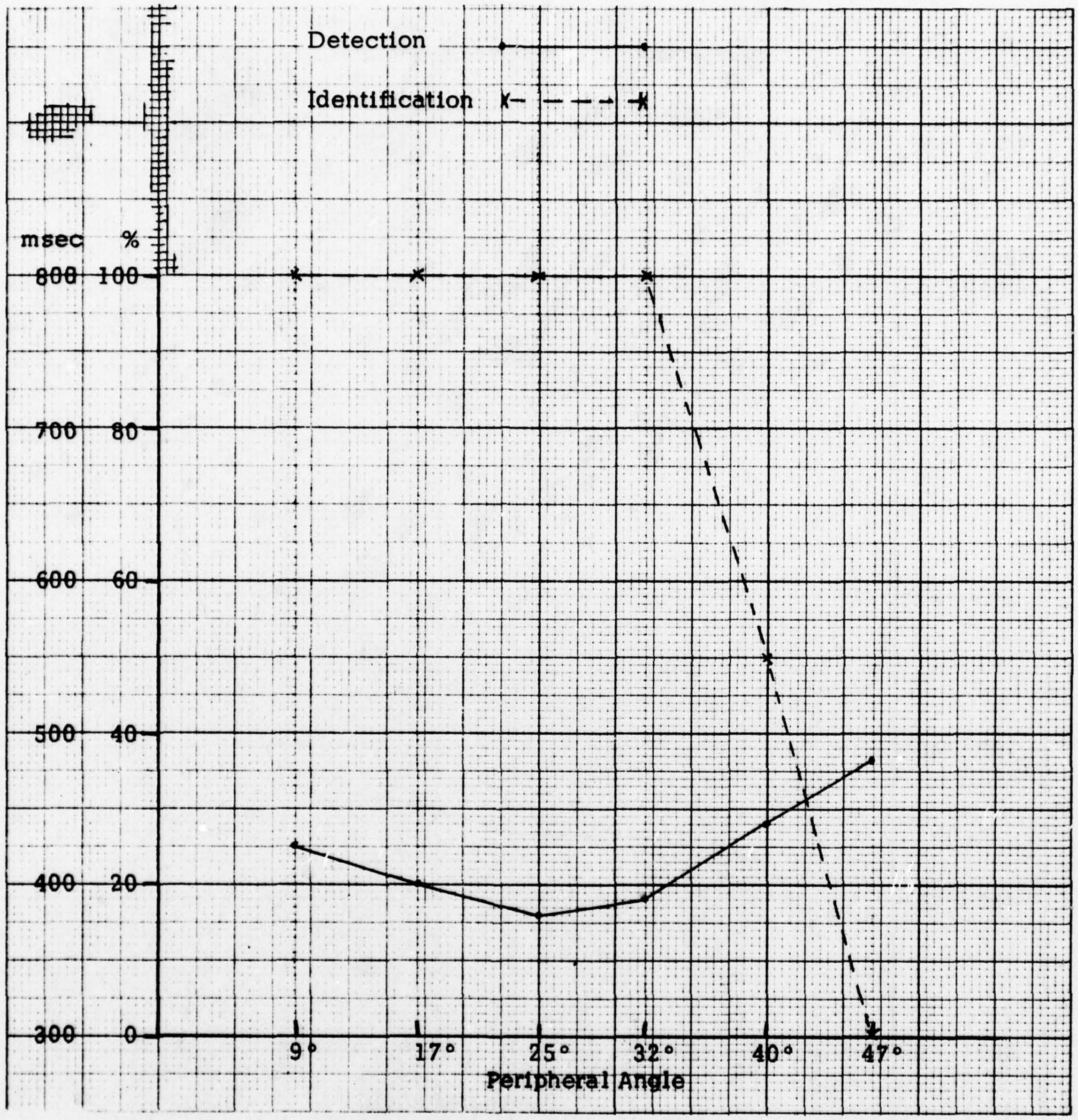

Figure 14. Detection and Identification Performance Effectiveness As A Function of Peripheral Angle in 'Ocean' Turbidity: Green Display at 0.03 ft-L

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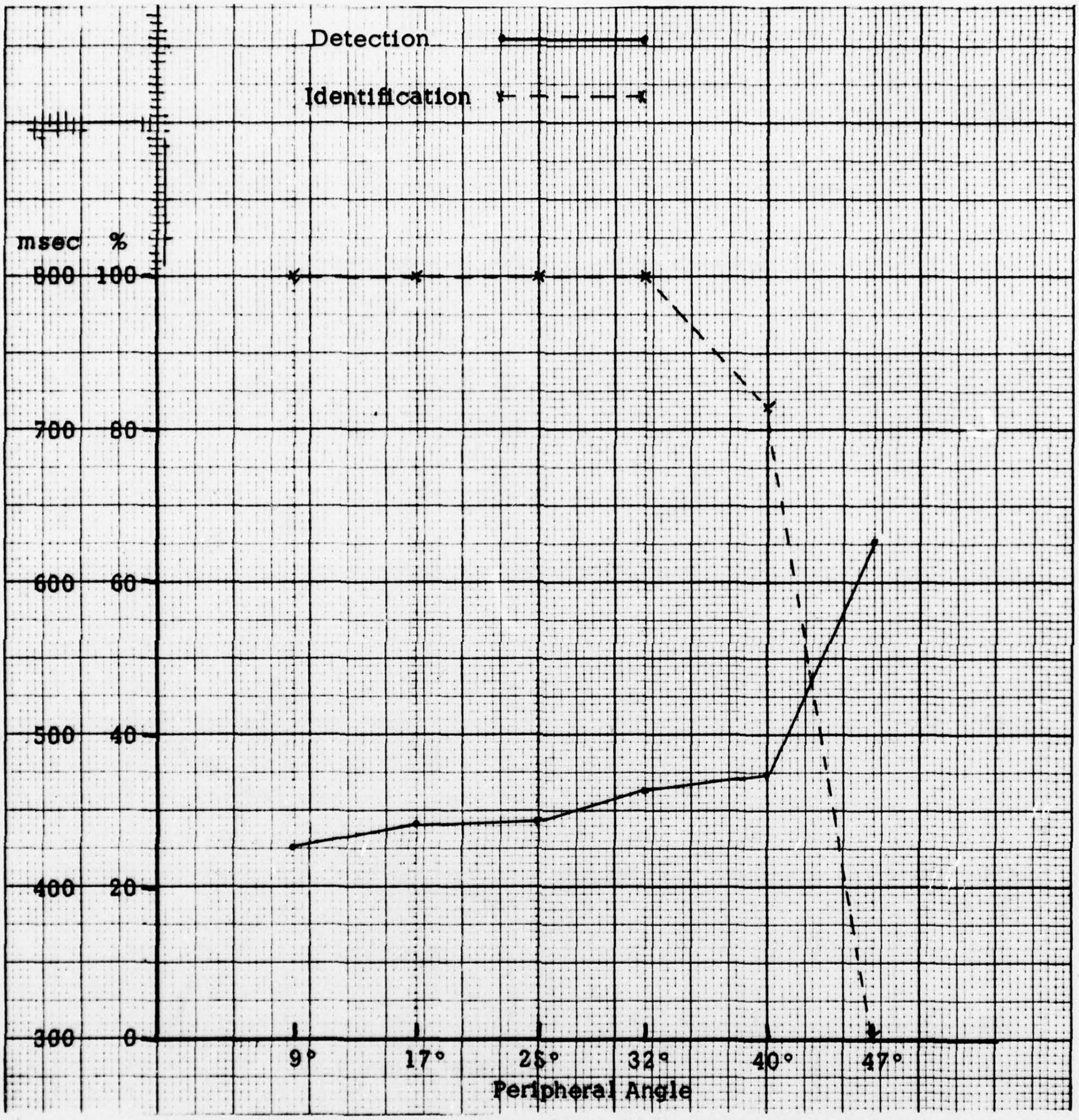

Figure 15. Detection and Identification Performance Effectiveness As A Function of Peripheral Angle in 'Ocean' Turbidity: Red Display at 0.1 ft-L

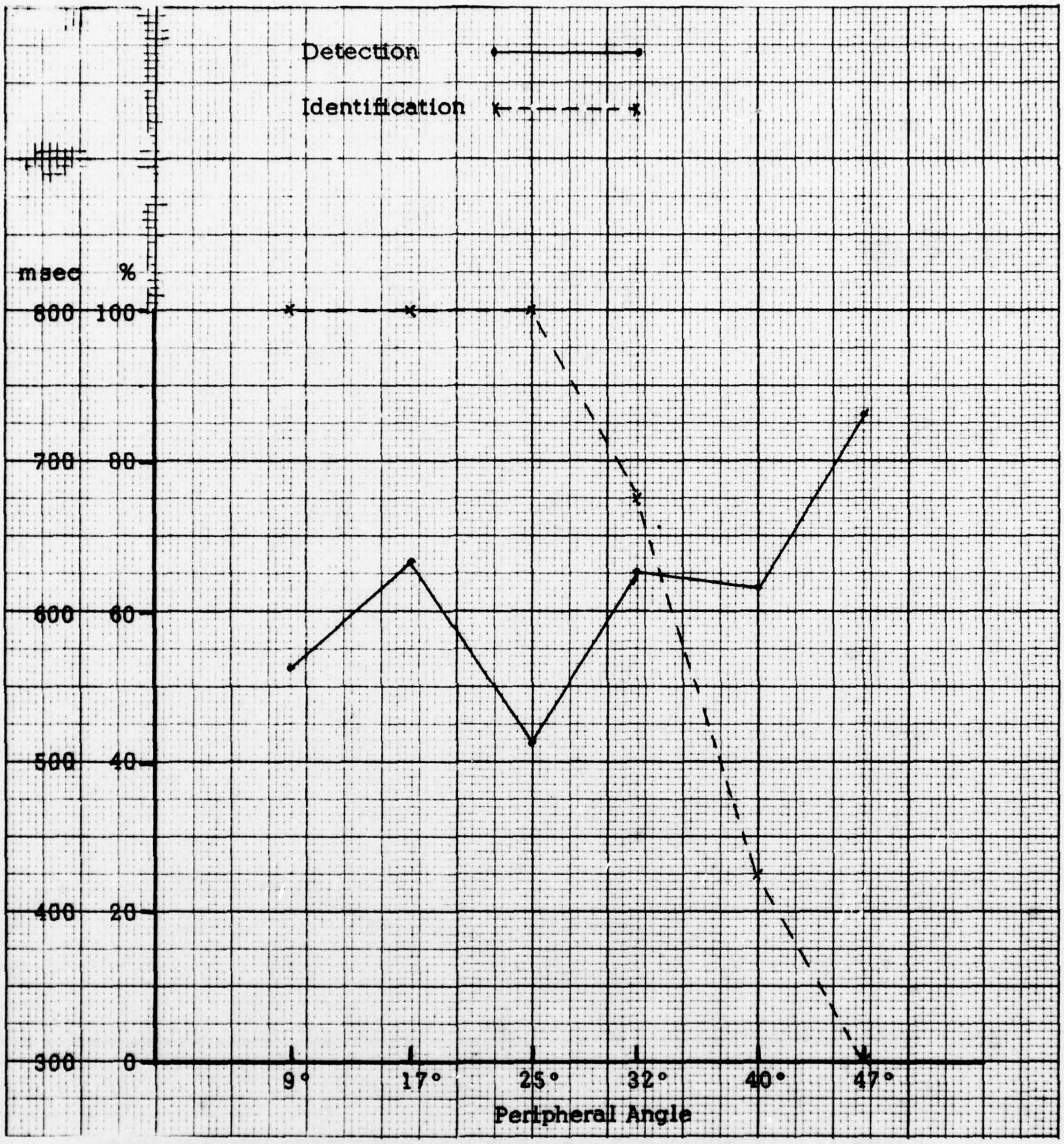

Figure 16. Detection and Identification Performance Effectiveness As A Function of Peripheral Angle in 'Ocean' Turbidity: Red Display at 0.03 ft-L

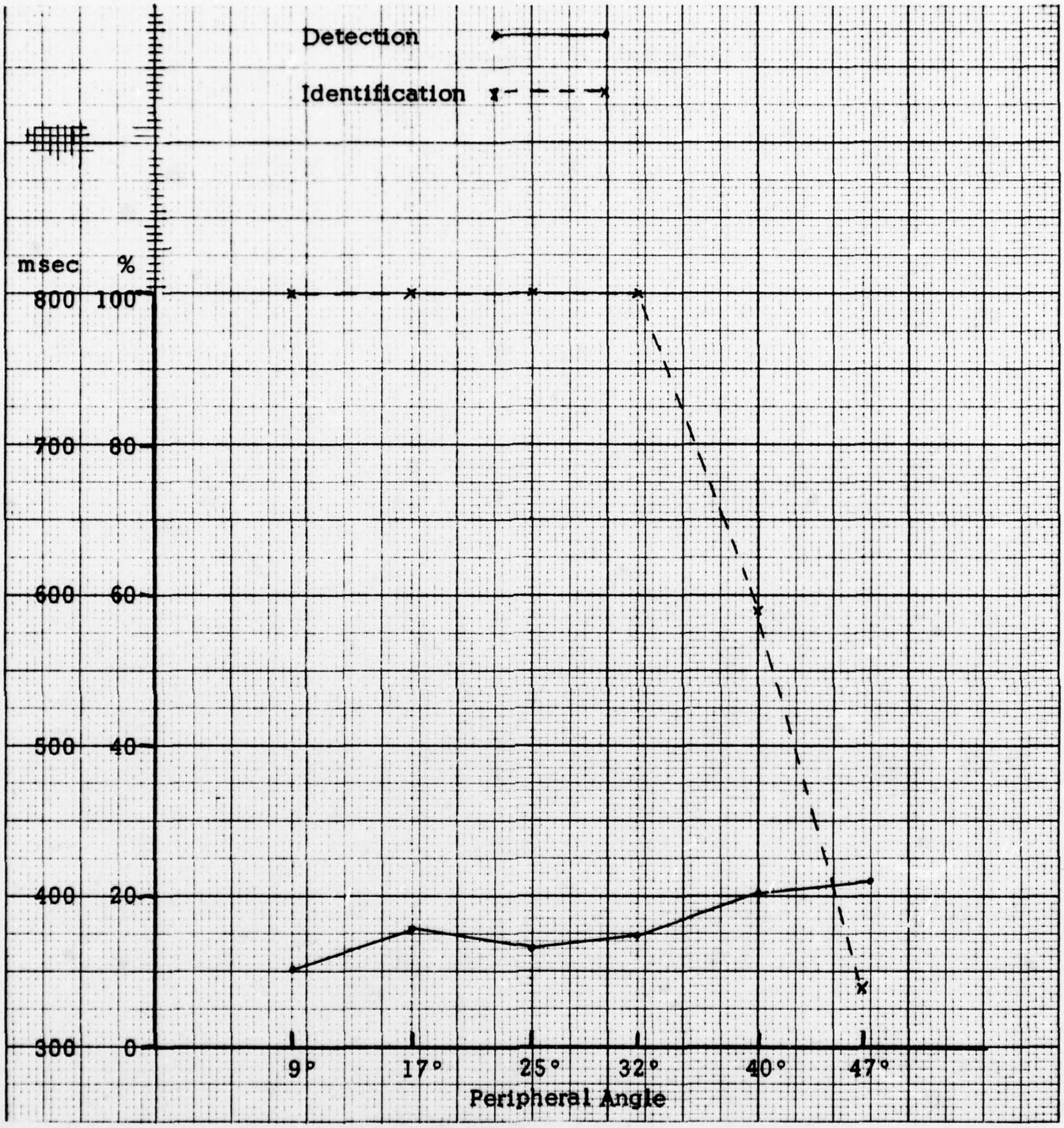

Figure 17. Detection and Identification Performance Effectiveness
As A Function of Peripheral Angle
in 'Harbor' Turbidity: Green Display at 100 ft-L

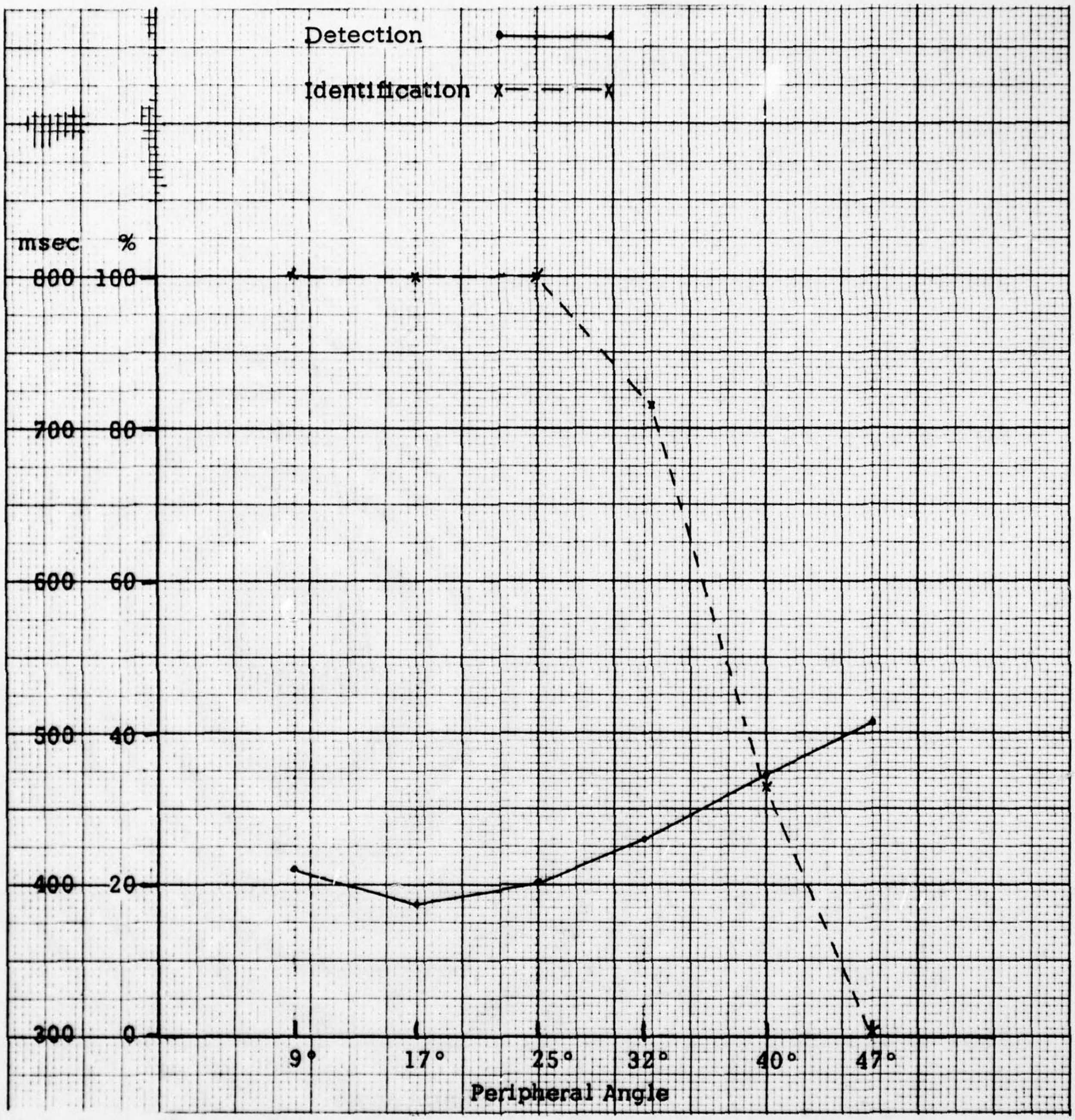

Figure 18. Detection and Identification Performance Effectiveness As A Function of Peripheral Angle in 'Harbor' Turbidity: Green Display at 30 ft-L

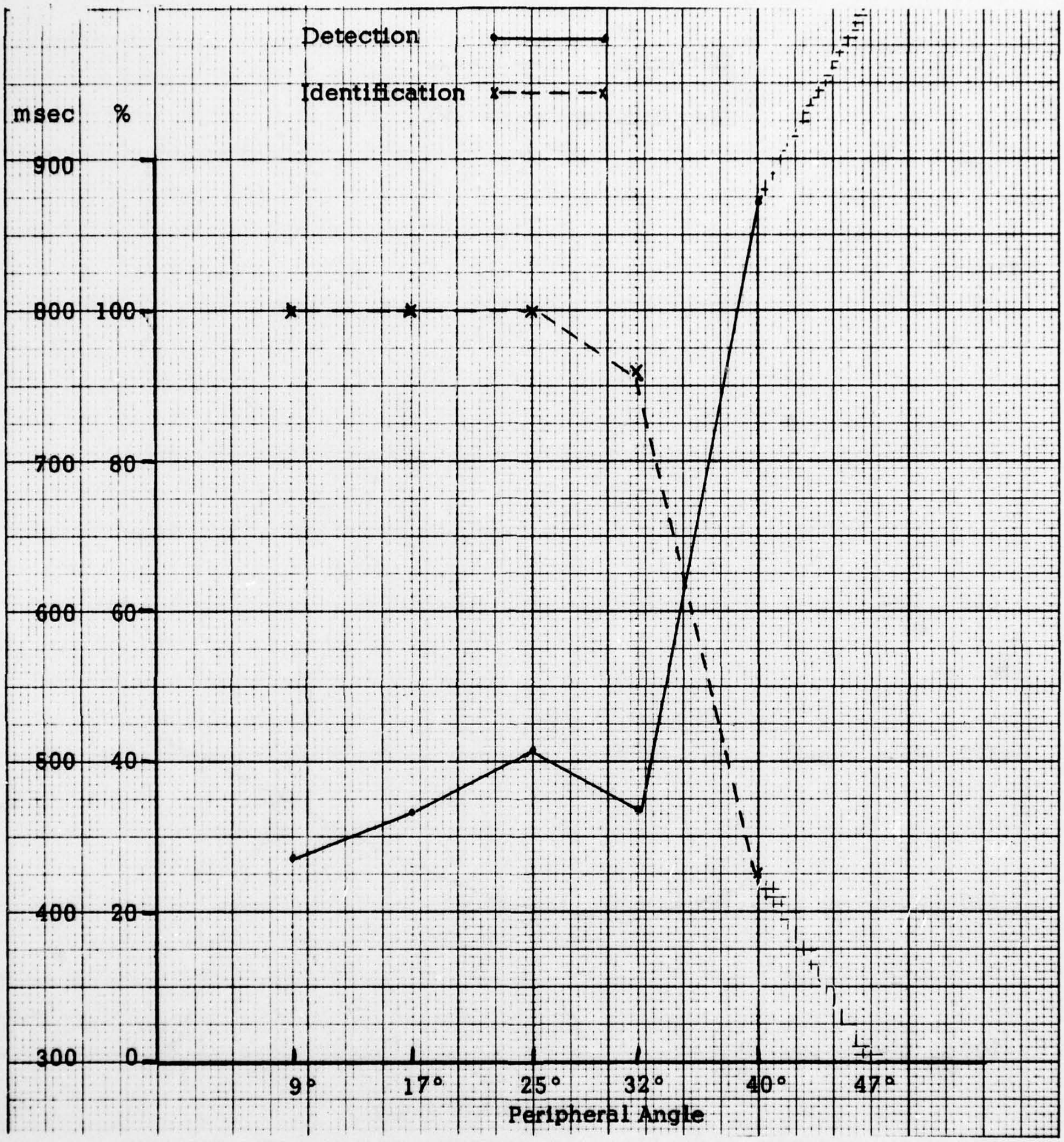

Figure 19. Detection and Identification Performance Effectiveness As A Function of Peripheral Angle in 'Harbor' Turbidity: Red Display at 100 ft-L

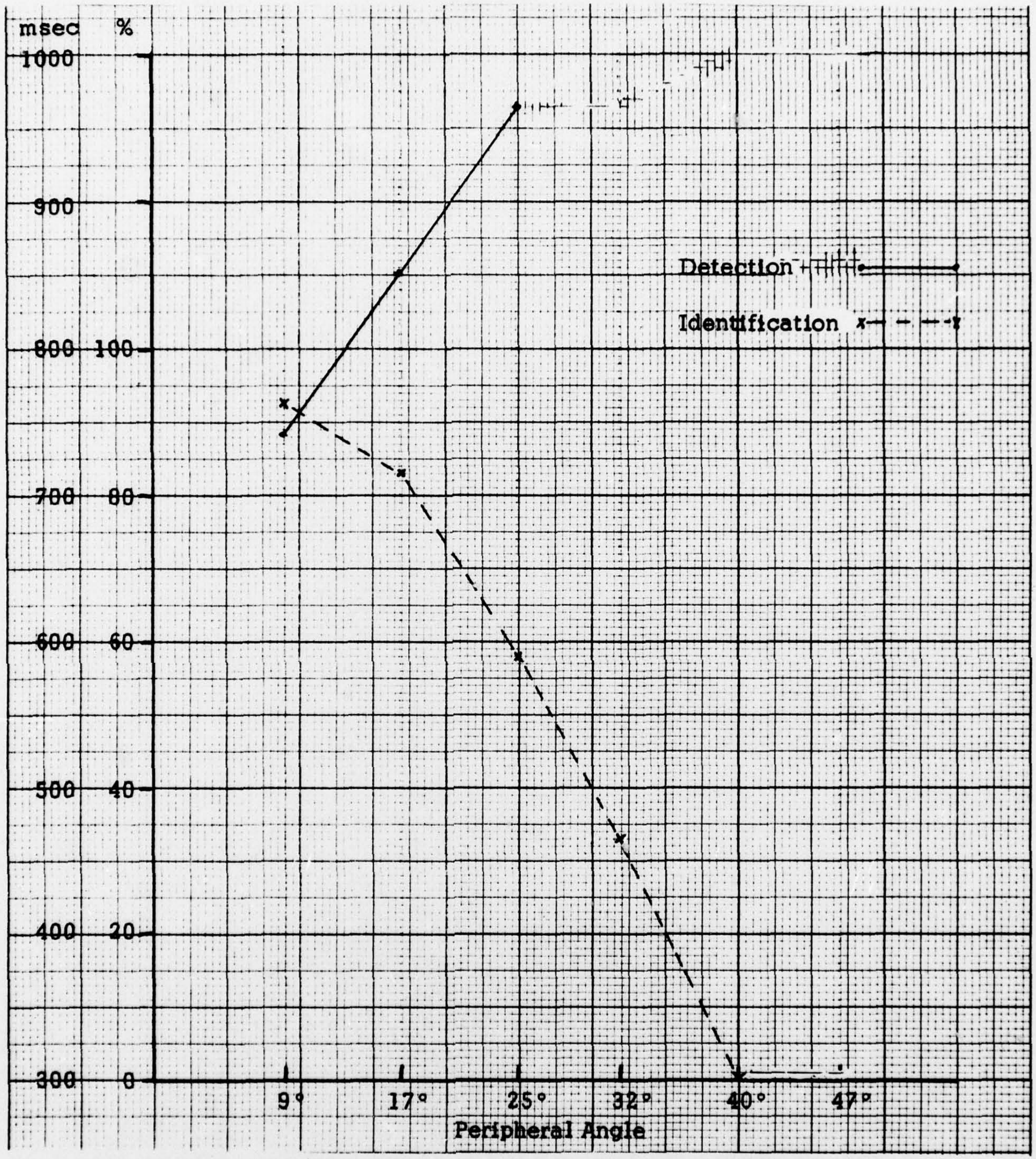

Figure 20. Detection and Identification Performance Effectiveness As A Function of Peripheral Angle in 'Harbor' Turbidity: Red Display at 30 ft-L

IV. GENERALIZATIONS AND IMPLICATIONS FOR CONSOLE DESIGN

The results of this experiment were intended to provide guidance to designers of displays for underwater applications. The scope of the design problem area investigated was the utility of the peripheral visual field for detection and identification tasks in 'Ocean' and 'Harbor' viewing environments. The context within which these problem areas were addressed involved a dark-adapted observer, engaged in a continuous tracking task which maintained his attention on a centrally located display. The results of the experiments were expected to provide two kinds of guidance: relative advantages of variations in display characteristics, and absolute limits on peripheral usefulness for 'best case' combinations of characteristics within the range of values included in the experiment. Of particular concern was the effect of variations in turbidity characterizing the viewing environments represented as 'Ocean' and 'Harbor'.

From the complex sets of interactions among viewing environments, visual tasks and display characteristics presented in the preceding section, certain regularities emerge as generalizations; and since this section of the report is intended principally as an aid to a display designer, the generalizations are organized from the perspective of a designer's options.

A. Generalizations About Display Characteristics

1. Display Color

The principal effect of Red vs Green variations in display color was on the peripheral detection task. Display color made small but consistent differences in the 'Ocean' and large consistent differences in the 'Harbor' viewing environments; always in favor of Green, and only when the detection task was examined.

2. Console Distance

The principal effect of variations in eye-to-console distance as a determinant of peripheral effectiveness was on the identification task. Again, in the 'Ocean', identification accuracy decreased by small percentages and in the 'Harbor' by large percentages as console distance increased. At high display luminance and with data aggregated over angles and colors, identification accuracy decreased 100%, 95%, 88% in the 'Ocean' and 100%, 84%, 10% in the 'Harbor' at console distances of 25, 35 and 45 cm.

3. Display Luminance

Luminance requirements for superthreshold foveal identification in 'Ocean' vs 'Harbor' turbidity conditions are magnitudes apart; 0.1 ft-L is an adequate stimulus in the 'Ocean', 100 ft-L in the 'Harbor' simulations. The principal generalization regarding display luminance from the results of this experiment is the significant reduction of peripheral effectiveness when red light is made less bright in 'Harbor' turbidity. In the relatively clear water of the 'Ocean' simulation, reduced luminance had no effect on the identification task, but red was consistently less effective than green for peripheral detection.

Reducing display luminance in the turbid 'Harbor' environment, however, had a dramatic impact on the relative effectivness of Red vs Green display colors for both visual tasks. For example, at 30 ft-L display luminance, 56% of all peripheral presentations of red light resulted in a 'No Response'; peripheral presentations of green light at 30 ft-L not only resulted in zero 'No Response' trials but the overall mean reaction times were comparable to those obtained at 100 ft-L (435 vs 380 msec).

B. Console Design Recommendations

Within the limits of the variables included in the experiment, peripheral utility was maximized by high-luminance, green displays. In no case was low luminance an improvement over high, and in no case was red color an

improvement over green. The issue regarding console distance was not so clear cut, far distances favored by the 'Ocean' data, near distances by the 'Harbor'. As an aid to this design decision involving compromise among conflicting maximizing principles, Table 11 was constructed. Table 11 includes only data from the High Luminance, Green Color display combination since these were optimal design choices. The table shows those peripheral angles, and their corresponding linear distances along the horizontal axis of the console, at which criterion levels of performance were maintained. Performance criteria were selected as a reaction time of less than 500 msec for the detection task, and an accuracy of 90% or greater for the identification task. The three console distances and the two viewing environments are included as the columns and rows of the table.

Peripheral angles were translated into linear distance from line-of-sight for a given angle at a given console distance. The designer's goal is assumed to be to choose a console distance which yields the widest effective console; thereby enabling him to place more displays within the effective visual field. Since the lateral distance from the tracking display varied with peripheral angle as eye-to-console distance increased, the lateral distance value was used as the basis for evaluating Console Distance. Figure 21 shows the lateral distances along the console face for combinations of peripheral angle and eye-to-console distance.

Examination of the lateral distance data in Table 11, leads to the choice of 35 cm as the optimal Console Distance. The shorter Console Distance, 25 cm, narrows the useful console space to 11-5/8" vs 14-3/4+" for either 35 or 45 cm. (The '+' sign indicates criterion level performance to the limits of the variable included in the experiment. Presumably the true peripheral limit is in excess of 14-3/4" at 35 cm console distance.) The further Console Distance, 45 cm, practically eliminates the peripheral utility for the identification task in the 'Harbor'.

Given the combination of High Luminance, Green Color displays at a Console Distance of 35 cm, peripheral signals will be detected if placed within 14-3/4" of the central display. Digital displays can be accurately read if placed within 8>1/2" of the central display of the console. The effective lateral dimension of the console (assuming the central display in the center of the console) is 29-1/2".

Table 11. Peripheral Limits to Criterion Levels of Detection and Identification Tasks for A High-Luminance, Green Display

		Detection (RT < 500 msec)			Identification (Accuracy > 90%)		
		At 25 cm	At 35 cm	At 45 cm	At 25 cm	At 35 cm	At 45 cm
'Ocean' Viewing Environment	Peripheral Angle	50°	47°+	40°+	41°	32°	33°
	Lateral distance from central display	11-5/8"	14-3/4"+	14-3/4"+	8-1/2"	8-1/2"	11-5/8"
'Harbor' Viewing Environment	Peripheral Angle	50°	47°+	40°+	41°	32°	<7°
	Lateral distance from central display	11-5/8"	14-3/4"+	14-3/4"+	8-1/2"	8-1/2"	-

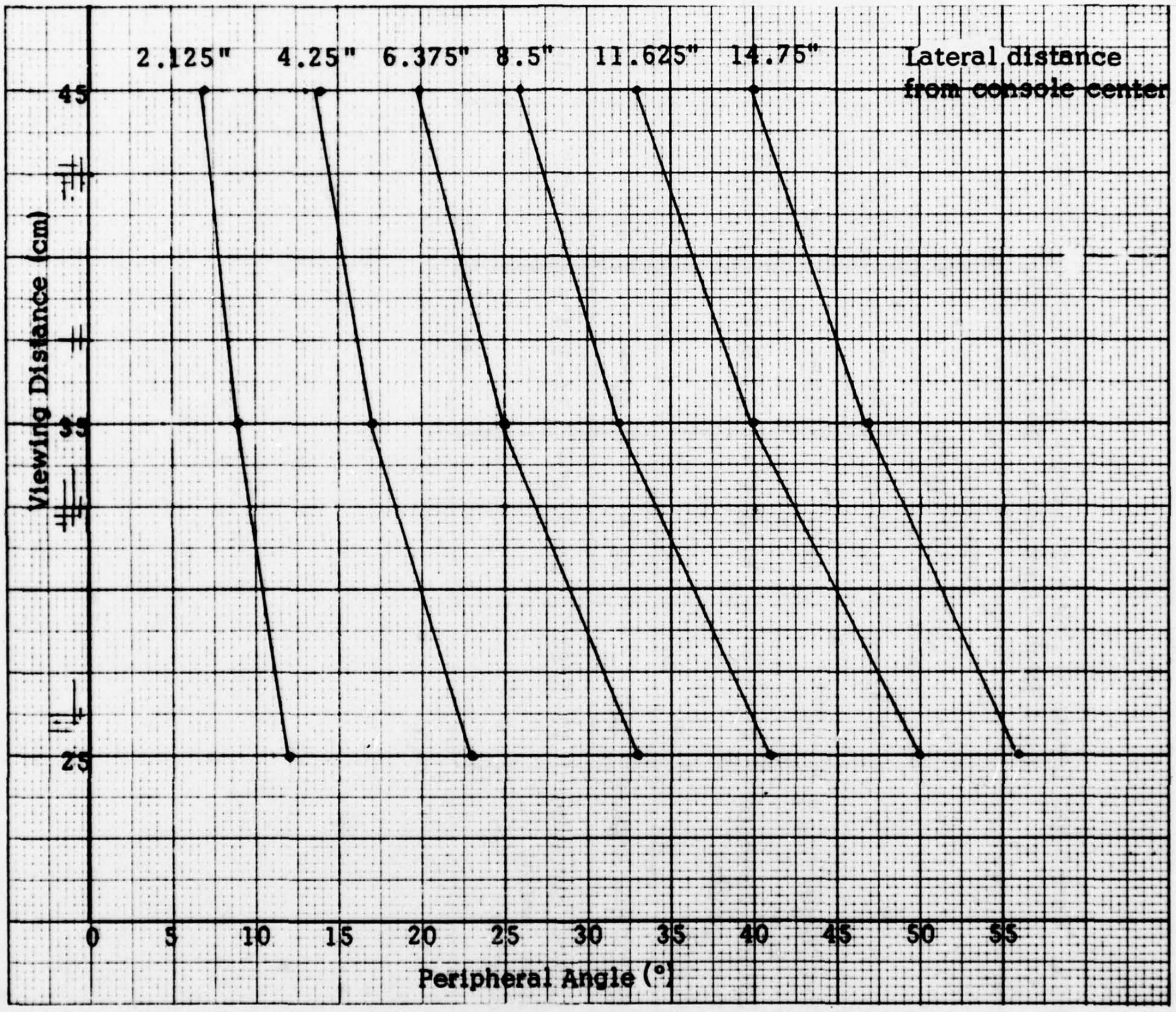

Figure 21. Lateral Distance at the Console for Combinations of Eye-to-Console Distance and Peripheral Angle

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APPENDIX A

OPTICAL DENSITY MEASUREMENTS AND ANALYSES OF 'OCEAN' AND 'HARBOR' TURBIDITY SIMULATIONS

Measurements of optical density as a function of wavelength for samples of 'Ocean' and 'Harbor' turbidity simulations are tabled in Tables A-1 and A-2. Four samples of the experimental viewing environments were taken during the data collection interval: 13-21 June 1977 for the 'Ocean' trials and 27 June-12 July 1977 for the 'Harbor'. Figures A-1 and A-2 are plots of the optical density x wavelength functions. Each of the viewing environments were fairly consistent in optical properties over the testing interval with the exception of one day's sample: 13 June for the 'Ocean' condition and 29 July for the 'Harbor'. The average standard duration of the optical density measures for the the eleven wavelengths was .076 in the 'Ocean' which was 18% of the mean. In the 'Harbor' condition, the average standard deviation was .170 or 25% of the mean of the optical density measurements.

Tables A-3 and A-4 compare the optical properties of the 'Ocean' and 'Harbor' waters used as experimental viewing environments in 1977 with those prepared for the 1976 legibility experiments. Both comparisons show the 1977 samples to be approximately .05 units less dense than the artificially turbid water samples of 1976 and could easily be accounted for by variations in the tap water at the test site from one year to the next.

[redacted]

Table A-1. Optical Density of 'Ocean' Turbidity Simulations*

Wavelength (nm)	Sampling				Mean	S.D.
	13 June 77	15 June 77	20 June 77	22 June 77		
500	.0670	.0888	.0877	.1023	.0865	.0146
510	.0649	.0856	.0867	.0996	.0842	.0144
520	.0624	.0819	.0851	.0974	.0817	.0145
530	.0594	.0803	.0819	.0942	.0790	.0144
540	.0579	.0772	.0809	.0915	.0769	.0140
550	.0560	.0757	.0793	.0893	.0751	.0140
560	.0550	.0731	.0777	.0867	.0731	.0133
570	.0535	.0710	.0757	.0856	.0715	.0134
580	.0515	.0690	.0741	.0835	.0695	.0134
590	.0506	.0665	.0726	.0814	.0678	.0130
600	.0501	.0655	.0716	.0809	.0670	.0129

*Optical Density = $\log \left(\frac{100}{\%T}\right)$; where %T = percent of incident light transmitted through a 10 cm path length of turbid water as compared to a 10 cm path of distilled water.

Table A-2. Optical Density of 'Harbor' Turbidity Simulations

Wavelength (nm)	Sampling				Mean	S.D.
	27 June 77	29 June 77	6 July 77	12 July 77		
500	.7772	.4509	.6925	.8632	.6960	.1776
510	.7746	.4461	.6840	.8601	.6912	.1785
520	.7695	.4424	.6777	.8538	.6859	.1775
530	.7594	.4388	.6736	.8477	.6799	.1757
540	.7447	.4317	.6595	.8386	.6686	.1741
550	.7375	.4282	.6516	.8239	.6603	.1700
560	.7212	.4213	.6420	.8153	.6500	.1681
570	.7166	.4156	.6326	.8013	.6415	.1656
580	.7033	.4100	.6216	.7958	.6327	.1646
590	.6925	.4023	.6126	.7772	.6212	.1606
600	.6777	.3946	.6020	.7644	.6097	.1580

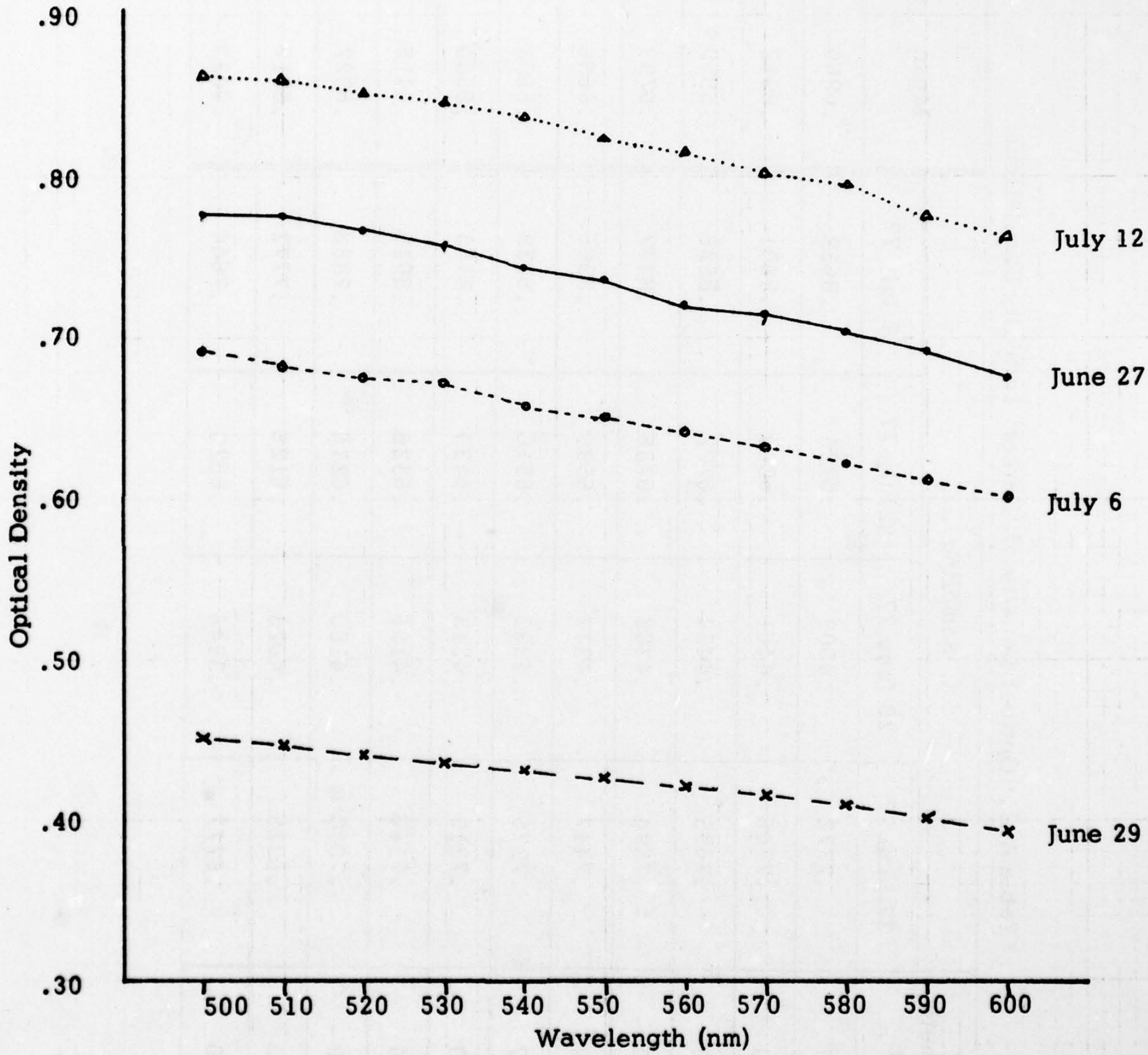

Figure A-1. Optical Density vs Wavelength for Four Samples of 'Ocean' Turbidity

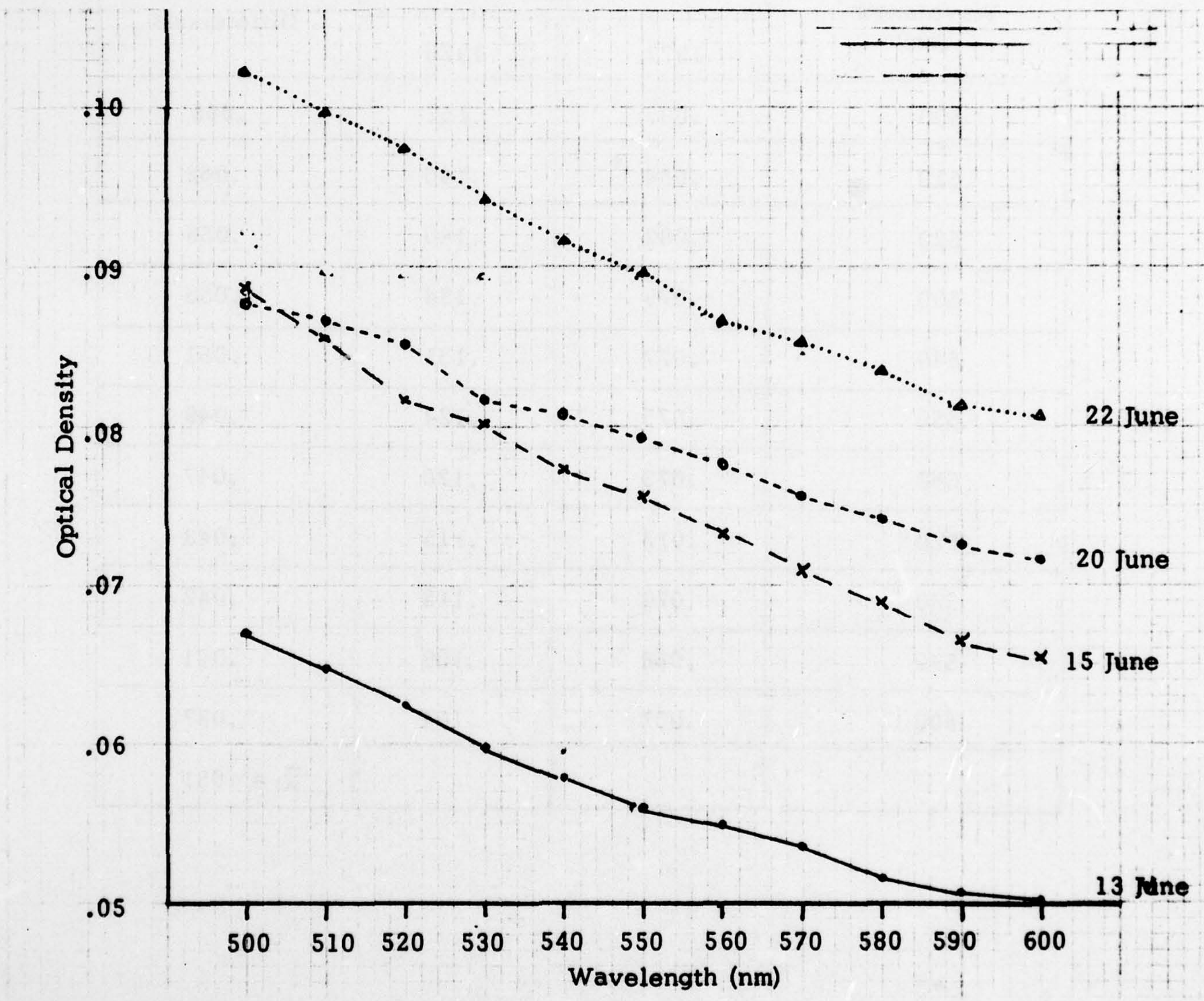

Figure A-2. Optical Density vs Wavelength for Four Samples of 'Harbor' Turbidity

Table A-3. Mean Optical Density at Selected Wavelengths for Samples of Artificially Turbid 'Ocean' Water Prepared in 1976 and 1977

Wavelength (nm)	Year		Differences
	1977	1976	
500	.087	.152	.065
510	.084	.146	.062
520	.082	.140	.058
530	.079	.134	.055
540	.077	.131	.061
550	.075	.124	.049
560	.073	.120	.047
570	.072	.115	.043
580	.070	.112	.042
590	.068	.109	.041
600	.067	.104	.037
			$\overline{X}$ = .051

Table A-4. Mean Optical Density at Selected Wavelengths for Samples of Artificially Turbid 'Harbor' Water Prepared in 1976 and 1977

Wavelength (nm)	Year		Differences
	1977	1976	
500	.696	.748	.052
510	.691	739	.048
520	.686	.735	.049
530	.680	.726	.046
540	.669	.721	.052
550	.660	.711	.051
560	.650	.700	.050
570	.642	.688	.046
580	.633	.682	.049
590	.621	.670	.049
600	.610	.661	.051
			$\overline{X}$ = .049

APPENDIX B

TEST PARTICIPANTS

Name	Rank/Rate
Foreman, David E.	LT(jg)
Hall, John F.	BT2
Hawkins, Thomas L.	LCDR
Hersh, Daniel W.	QMSN
Jaquith, Greg E.	EM3
Klingensmith, James M.	QM3
May, Rick A.	AE2
Mitchell, Robert A.	ABFAN
Peterman, Robert C.	ENS
Rohling, Henry J.	LT(jg)
Sayre, Donald L.	GMG2
Shoulders, Thomas M.	QMC
Springer, Theodis	YN3
Warner, Ronald H.	AE3

[redacted]

APPENDIX C

BASIC DATA TABLES FOR DETECTION SPEED

Cell entries are simple reaction times in msec.

Table C-1. Reaction Time Data: 'Ocean' Turbidity

Observer	25 cm Viewing Distance - .1 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	12°	23°	33°	41°	50°	56°	12°	23°	33°	41°	50°	56°
1	389	493	418	496	495	594	467	554	472	506	467	496
2	376	323	338	368	364	601	422	367	356	379	440	444
3	312	391	398	383	453	800	375	343	354	394	467	376
4	374	435	439	392	496	607	402	470	480	505	531	490
5	269	285	346	339	320	463	395	308	323	339	391	340
6	374	358	313	358	415	380	451	463	427	437	1532	454
7	367	352	295	328	371	494	393	402	452	468	NR	NR
8	425	430	420	447	402	662	454	441	485	537	592	527
9	447	326	499	319	511	606	429	557	388	454	611	670
10	300	395	351	371	445	514	454	465	438	468	446	500
11	336	353	351	336	333	456	348	441	449	503	480	875
12	476	531	648	605	566	1001	497	459	509	685	1133	682

[redacted]

Table C-1. Reaction Time Data: 'Ocean' Turbidity (Continued)

Observer	35 cm Viewing Distance - .1 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1	507	426	541	412	393	636	457	476	394	484	432	511
2	338	325	360	310	286	370	320	369	330	387	441	447
3	468	484	502	386	419	548	442	364	468	377	384	359
4	573	383	572	387	455	439	536	461	455	704	449	874
5	339	291	287	256	287	356	351	348	368	298	408	362
6	366	359	336	340	402	423	365	357	475	457	476	361
7	311	327	429	282	355	432	344	606	534	349	574	NR
8	365	357	436	389	422	399	499	410	503	491	455	601
9	365	413	366	392	434	486	416	395	456	453	475	789
10	346	354	315	362	306	373	409	504	442	498	421	811
11	288	299	368	325	438	349	441	415	437	512	383	585
12	501	604	568	679	443	904	544	602	471	563	765	811

Table C-1. Reaction Time Data: 'Ocean' Turbidity (Continued)

Observer	35 cm Viewing Distance - .03 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1	482	419	336	385	389	479	583	472	489	726	517	446
2	309	376	337	367	391	421	365	480	421	456	346	1256
3	472	388	389	369	451	392	474	461	409	437	418	431
4	478	408	404	424	461	540	612	605	571	568	865	868
5	364	316	299	286	331	317	405	368	320	402	376	377
6	361	369	335	329	379	381	449	666	500	550	486	NR
7	364	389	360	400	410	427	469	584	443	492	483	627
8	415	444	398	402	442	467	484	482	486	569	631	629
9	507	432	496	395	499	514	890	1272	659	969	937	901
10	411	388	315	368	403	482	634	585	535	704	686	690
11	311	341	331	391	387	481	552	898	609	650	660	786
12	651	555	559	594	752	900	724	1495	718	1183	1754	1185

Table C-1. Reaction Time Data: 'Ocean' Turbidity (Continued)

Observer	45 cm Viewing Distance - .1 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	7°	14°	20°	26°	33°	40°	7°	14°	20°	26°	33°	40°
1	408	547	503	426	520	475	430	492	482	521	394	477
2	334	336	355	329	367	323	413	386	411	423	410	434
3	318	353	366	335	514	383	432	313	476	387	382	346
4	498	452	464	520	565	575	588	661	555	538	634	784
5	303	311	320	300	330	319	387	376	345	341	311	335
6	393	306	347	359	335	356	369	368	454	422	450	428
7	327	356	430	359	330	361	498	482	566	543	559	1526
8	347	391	391	360	396	402	460	453	471	484	361	485
9	401	507	546	353	591	439	486	464	463	428	535	553
10	374	408	398	384	476	389	464	497	469	502	415	588
11	336	353	351	336	333	456	412	482	499	452	413	463
12	571	602	593	620	616	689	601	822	570	648	840	860

Table C-2. Reaction Time Data: 'Harbor' Turbidity

Observer	25 cm Viewing Distance - 100 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	12°	23°	33°	41°	50°	56°	12°	23°	33°	41°	50°	56°
1	381	480	388	403	416	478	479	436	394	410	NR	NR
2	281	235	270	251	298	362	284	281	291	329	379	NR
3	247	289	378	281	291	373	281	330	352	389	1603	NR
4	487	601	556	556	579	1806	544	671	420	436	735	NR
5	240	247	203	259	273	326	333	309	321	346	409	NR
6	258	265	256	277	316	323	287	301	309	386	653	NR
7	296	295	302	316	322	341	294	334	349	370	NR	NR
8	413	405	412	373	461	546	337	374	388	385	608	NR
9	528	618	482	495	442	511	407	549	646	444	818	NR
10	239	294	260	318	289	472	297	328	320	394	1074	NR
11	282	329	300	299	379	427	298	349	364	400	NR	NR
12	396	593	465	532	456	546	452	524	463	558	NR	NR

Table C-2. Reaction Time Data: 'Harbor' Turbidity (Continued)

Observer	35 cm Viewing Distance - 100 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1	437	406	377	512	431	523	469	457	603	540	624	NR
2	293	343	278	262	354	368	433	362	379	338	NR	NR
3	262	279	267	316	448	329	433	589	429	485	1714	NR
4	471	468	550	438	501	446	591	660	608	435	2374	NR
5	234	228	276	267	303	346	321	344	365	324	593	NR
6	291	263	273	316	347	285	323	401	476	422	NR	NR
7	314	310	307	256	271	311	340	466	393	383	600	NR
8	450	402	427	442	461	542	413	489	479	437	639	NR
9	449	527	433	377	556	570	509	567	713	476	NR	NR
10	265	333	363	336	290	396	419	418	455	673	NR	NR
11	310	403	354	424	360	351	327	378	472	367	NR	NR
12	435	583	485	541	505	451	650	462	731	732	NR	NR

Table C-2. Reaction Time Data: 'Harbor' Turbidity (Continued)

Observer	35 cm Viewing Distance - 30 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1	555	424	527	554	830	610	1000	632	1029	713	NR	NR
2	282	312	278	303	295	320	558	520	565	865	NR	NR
3	355	309	323	337	388	389	451	1114	NR	NR	NR	NR
4	660	536	525	749	875	877	747	941	2191	1847	NR	NR
5	270	276	300	307	334	332	713	471	1833	NR	NR	NR
6	317	319	305	313	273	328	551	NR	NR	NR	NR	NR
7	308	270	263	280	264	349	NR	NR	NR	NR	NR	NR
8	462	430	411	447	523	580	702	978	1564	994	NR	NR
9	557	602	554	542	497	586	1027	1428	NR	NR	NR	NR
10	325	318	381	344	359	350	736	940	1561	NR	NR	NR
11	319	326	377	393	375	380	553	725	1525	NR	NR	NR
12	527	520	571	587	661	1051	922	1309	NR	NR	NR	NR

Table C-2. Reaction Time Data: 'Harbor' Turbidity (Continued)

Observer	45 cm Viewing Distance - 100 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	7°	14°	20°	26°	33°	40°	7°	14°	20°	26°	33°	40°
1	455	429	434	460	375	615	734	506	544	664	NR	NR
2	298	319	325	306	310	416	520	563	513	600	829	NR
3	291	275	312	276	428	360	592	656	2626	890	NR	NR
4	457	564	993	434	451	666	678	884	2162	1654	NR	NR
5	225	243	249	250	250	274	475	445	706	964	NR	NR
6	282	254	311	267	270	319	528	456	1467	NR	NR	NR
7	317	276	291	333	352	302	490	523	NR	NR	1343	NR
8	430	444	464	484	521	468	567	578	655	540	NR	NR
9	931	594	743	758	688	1157	748	1721	1141	1114	NR	NR
10	370	282	395	390	373	386	792	NR	NR	NR	NR	NR
11	313	343	345	339	329	391	457	463	512	NR	NR	NR
12	566	524	673	626	706	430	784	619	NR	NR	NR	NR

APPENDIX D

BASIC DATA TABLES FOR IDENTIFICATION ERROR

Blank cells are correct responses; error data are coded as NS, not seen within 3000 msec; NR, seen but no attempt at identification; RE, incorrect identification.

Table D-1. Identification Error Data: 'Ocean' Turbidity

Observers	25 cm Viewing Distance - .1 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	12°	23°	33°	41°	50°	56°	12°	23°	33°	41°	50°	56°
1						NR					NR	NR
2						NR					NR	NR
3						NR						NR
4						NR						NR
5						NR					NR	NR
6					NR	NR					NR	NR
7					NR	NR					NS	NS
8					NR	NR					NR	NR
9						NR					NR	NR
10					NR	NR					NR	NR
11						NR					NR	NR
12					NR	NR					NR	NR

Table D-1. Identification Error Data: 'Ocean' Turbidity (Continued)

Observers	35 cm Viewing Distance - .1 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1												NR
2												NR
3						RE						NR
4						RE						NR
5						RE						NR
6					RE	NR						NR
7					NR	NR					NR	NS
8					RE	NR						NR
9						RE						NR
10						NR					NR	NR
11						RE						NR
12						NR						NR

Table D-1. Identification Error Data: 'Ocean' Turbidity (Continued)

Observers	35 cm Viewing Distance - .03 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1						NR						NR
2						NR					NR	NR
3					RE	NR						NR
4					RE	NR						NR
5						NR				RE	RE	NR
6					RE	NR					NR	NS
7					NR	NR					NR	NR
8						NR				NR	NR	NR
9					RE	NR					NR	NR
10						NR					NR	NR
11						NR					NR	NR
12					RE	NR				NR	NR	NR

Table D-1. Identification Error Data: 'Ocean' Turbidity (Continued)

Observers	45 cm Viewing Distance - .1 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	7°	14°	20°	26°	33°	40°	7°	14°	20°	26°	33°	40°
1												
2												
3												
4												
5						RE						
6						NR						
7						NR						NR
8												NR
9												RE
10												NR
11												NR
12						RE					RE	NR

Table D-2. Identification Error Data: 'Harbor' Turbidity

Observer	25 cm Viewing Distance - 100 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	12°	23°	33°	41°	50°	56°	12°	23°	33°	41°	50°	56°
1					RE	NR					NS	NS
2						NR						NS
3						NR					NR	NS
4						NR						NS
5						NR						NS
6					NR	NR						NS
7					NR	NR					NS	NS
8					NR	NR					NR	NR
9						NR						NS
10						NR					NR	NS
11						NR					NS	NS
12					NR	NR					NS	NS

Table D-2. Identification Error Data: 'Harbor' Turbidity (Continued)

Observer	35 cm Viewing Distance - 100 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1					NR	NR						NS
2						NR					NS	NS
3						NR						NS
4					RE	NR						NS
5					RE	RE					NR	NS
6											NS	NS
7						NR				NR	NR	NS
8					NR	NR					NR	NR
9						NR					NS	NS
10						NR					NS	NS
11						NR					NS	NS
12					RE	NR					NS	NS

Table D-2. Identification Error Data: 'Harbor' Turbidity (Continued)

Observers	35 cm Viewing Distance - 30 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	9°	17°	25°	32°	40°	47°	9°	17°	25°	32°	40°	47°
1					RE	NR					NS	NS
2						NR					NS	NS
3						NR			NS	NS	NS	NS
4					NR	NR					NS	NS
5					RE	NR				NS	NS	NS
6						NR		NS	NS	NS	NS	NS
7						NR	NS	NS	NS	NS	NS	NS
8					NR	NR					NS	NS
9					RE	NR			NS	NS	NS	NS
10					NR	NR				NS	NS	NS
11				RE	NR	NR				NS	NS	NS
12				NR	NR	NR			NS	NS	NS	NS

Table D-2. Identification Error Data: 'Harbor' Turbidity (Continued)

Observers	45 cm Viewing Distance - 100 ft-L											
	Green Display						Red Display					
	Peripheral Angle						Peripheral Angle					
	7°	14°	20°	26°	33°	40°	7°	14°	20°	26°	33°	40°
1	NR	NR	NR	NR	NR	NR			NR	NR	NS	NS
2				NR	NR	NR				NR	NR	NS
3	RE	NR	NR	NR	NR	NR			NR	NR	NS	NS
4			NR	NR	NR	NR			NR	NR	NS	NS
5	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NS	NS
6		NR	NR	NR	NR	NR				NS	NS	NS
7		NR	RE	NR	NR	NR	NR	NR	NS	NS	NR	NS
8	NR	NR	NR	NR	NR	NR	RE	RE	NR	NR	NS	NS
9	NR	NR	NR	NR	NR	NR		NR	NR	NR	NS	NS
10	NR	RE	NR	NR	NR	NR	NR	NS	NS	NS	NS	NS
11	NR	NR	NR	NR	NR	NR	NR	NR	NR	NS	NS	NS
12	NR	NR	NR	NR	NR	NR	NR	NR	NS	NS	NS	NS

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Electromagnetics Technology Programs
Code 221
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

Defense Documentation Center
Cameron Station
Alexandria, Virginia 22314 (12 cys)

Director
Physiology Program
Code 441
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

Special Assistant for Marine Corps Matters
Code 100 M
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217

Commanding Officer
ONR Branch Office
ATTN: Dr. J. Lester
Building 114, Section D
666 Summer Street
Boston, Massachusetts 02210

Commanding Officer
ONR Branch Office
ATTN: Dr. C. Davis
536 South Clark Street
Chicago, Illinois 60605

Commanding Officer
ONR Branch Office
ATTN: Mr. R. Lawson
1030 East Green Street
Pasadena, California 91106

CDR Paul R. Chatelier
Military Assistant for Training and Personnel Technology
Office of the Deputy Under Secretary of Defense
OUSDRE (E&LS)
Pentagon, Room 3D129
Washington, D.C. 20301

Director
Code 2627
Naval Research Laboratory
Technical Information Division
Washington, D.C. 20375 (6 cys)

Dr. Robert G. Smith
Office of the Chief of Naval Operations, OP987H
Personnel Logistics Plans
Washington, D.C. 20350

CAPT James Barnes
Office of the Chief of Naval Operations
OP372G
Special Warfare
Washington, D.C. 20350

Mr. Arnold Rubinstein
Naval Material Command
NAVMAT 98T24
Washington, D.C. 20360

Mr. W. Greenert
Naval Material Command
NAVMAT 034
Hoffman II Building
200 Stovall Street
Alexandria, Virginia 22332

Mr. Glen R. Spalding
Naval Material Command
NAVMAT 08T245
Washington, D.C. 20350

Mr. Phillip Andrews
Naval Sea Systems Command
NAVSEA 0341
Washington, D.C. 20362

Dr. Jo Ann S. Kinney
Vision Branch
Naval Submarine Medical Research Laboratory
Naval Submarine Base
Groton, Connecticut 06340

Commander
Naval Sea Systems Command
NAVSEA 00C-DA
Washington, D.C. 20362

CAPT J. Vorosmarti
Naval Medical R&D Command
National Naval Medical Center
Bethesda, Maryland 20014

CDR R. Gibson
Code 513
Bureau of Medicine & Surgery
Aerospace Psychology Branch
Washington, D.C. 20372

LCDR Robert Biersner
Code 44
Naval Medical R&D Command
Naval Medical Center
Bethesda, Maryland 20014

Dr. Arthur Bachrach
Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, Maryland 20014

LCDR T. Berghage
Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, Maryland 20014

Dr. George Moeller
Human Factors Engineering Branch
Submarine Medical Research Lab
Naval Submarine Base
Groton, Connecticut 06340

Chief
Aerospace Psychology Division
Naval Aerospace Medical Institute
Pensacola, Florida 32512

Dr. Fred Muckler
Code 311
Navy Personnel Research & Development Center
Manned Systems Design
San Diego, California 92152

Dr. John Brady
Experimental Diving Unit
Department of the Navy
Panama City, Florida 32401

Mr. E. H. Freeman
Code 710
Room 1C22
Naval Coastal Systems Lab
Panama City, Florida 32401

Dr. Lloyd Hitchcock
Human Factors Engineering Division
Naval Air Development Center
Warminster, Pennsylvania 18974

Commander
ATTN: Code WU-102
Naval Surface Weapons Center
Silver Spring, Maryland 20910

Commanding Officer
Naval Explosive Ordnance Disposal Facility
Indian Head, Maryland 20640

Mr. J. Williams
Department of Environmental Sciences
U.S. Naval Academy
Annapolis, Maryland 21402

Human Factors Engineering Branch
Naval Ship Research and Development Center
Annapolis Division
Annapolis, Maryland 21402

Mr. John Quirk
Code 712
Naval Coastal Systems Laboratory
Panama City, Florida 32401

Dr. Jerry C. Lamb
Code TD112
Display Branch
Naval Underwater Systems Center
New London, Connecticut 06320

Human Factors Department
Code N215
Naval Training Equipment Center
Orlando, Florida 32813

Dr. Gary Poock
Operations Research Department
Naval Postgraduate School
Monterey, California 93940

Mr. H. Talkington
Ocean Engineering Department
Naval Ocean Systems Center
San Diego, California 92152

Mr. Paul Heckman
Naval Ocean Systems Center
San Diego, California 92152

Mr. Warren Lewis
Code 8231
Human Engineering Branch
Naval Ocean Systems Center
San Diego, California 92152

Dr. Ross L. Pepper
Naval Ocean Systems Center
Hawaii Laboratory
P.O. Box 997
Kailua, Hawaii 96734

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Code RD-1
Washington, D.C. 20380

Commander
Naval Special Warfare Group TWO
ATTN: RDT&E Officer
U.S. Naval Amphibious Base
Little Creek, Virginia 23521

Commanding Officer
Underwater Demolition Team 21
U.S. Naval Amphibious Base
Little Creek, Virginia 23521

Dr. Stephen J. Andriole
Director
Cybernetics Technology Office
Defense Advanced Research Projects Agency
1400 Wilson Boulevard
Arlington, Virginia 22209

U.S. Air Force Office of Scientific Research
Life Sciences Directorate, NL
Bolling Air Force Base
Washington, D.C. 20332

Dr. J. Miller
National Oceanic and Atmospheric Adminstration
11400 Rockville Pike
Rockville, Maryland 20852

Mr. John B. Gregory
Research Program Manager
Branch of Marine Oil and Gas Operations
U.S. Geological Survey
Reston, Virginia 22092

Technical Director
U.S. Army Human Engineering Labs
Aberdeen Proving Ground, Maryland 21005

Director
Organizations and Systems Research Laboratory
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, Virginia 22333

Dr. C. R. Cavonius
University of Dortmund
Dortmund, Germany

Dr. William H. Crooks
Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, California 91364

Dr. Glen Egstrom
Department of Kinesiology
University of California
Los Angeles, California 90024

Dr. Robert Fox
Department of Psychology
Vanderbilt University
Nashville, Tennessee 37240

Dr. Richard R. Rosinski
Department of Information Sciences
University of Pittsburgh
Pittsburgh, Pennsylvania 15260

Dr. T. B. Sheridan
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, Maryland 02139

Mr. Allan Slater
Senior Project Engineer
Emergency Care Research Institute
5200 Butler Pike
Plymouth Meeting, Pennsylvania 19462

Dr. Harry Snyder
Department of Industrial Engineering
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

Dr. William R. Uttal
Department of Psychology
Gartley Hall
University of Hawaii at Manoa
Honolulu, Hawaii 96822

LCDR Thomas L. Hawkins
Code 445
COMOPTEVFOR
U.S. Naval Operating Base
Norfolk, Virginia

Commanding Officer
Underwater Demolition Team 22
U.S. Naval Amphibious Base
Little Creek, Virginia 23521

Commanding Officer
SEAL TEAM TWO
ATTN: LT G. L. Stubblefield
U.S. Naval Amphibious Base
Little Creek, Virginia 23521

COMNAVSPECWAR Group One
ATTN: CDR I. C. LeMoyne
U.S. Naval Amphibious Base
Coronado, California

LCDR A. J. Sarich
U.S. Naval Academy
Annapolis, Maryland 21403

Mr. Charley Young
Code U102
Naval Surface Weapon Center
White Oak
Silver Spring, Maryland 20910